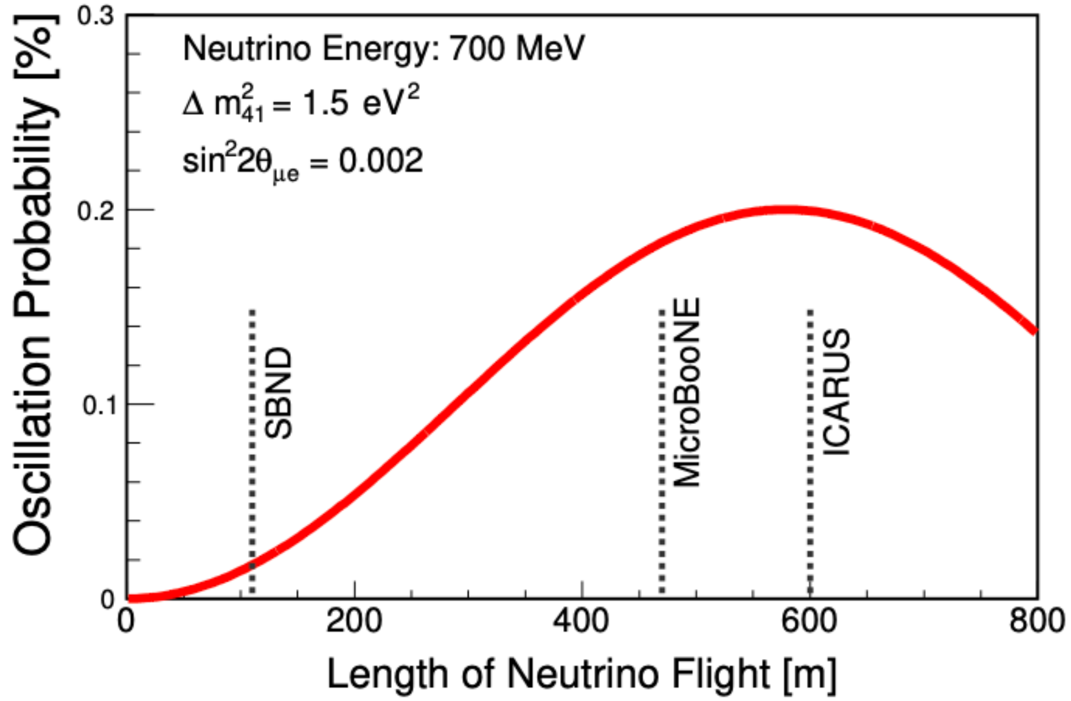
SBND-PRISM

Marco Del Tutto and Vishvas Pandey,
for the SBND collaboration

with Pedro Machado, Kevin Kelly, and Roni Harnik

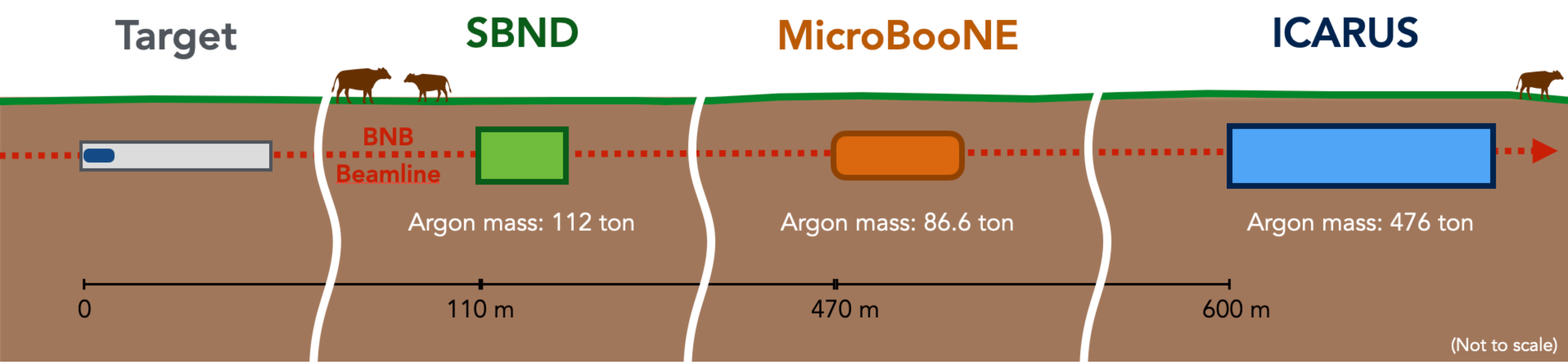
The SBN Program at Fermilab

✦ Three functionally identical Liquid Argon Time Projection Chamber (LArTPC) detectors located along the Booster Neutrino Beamline (BNB) at Fermilab



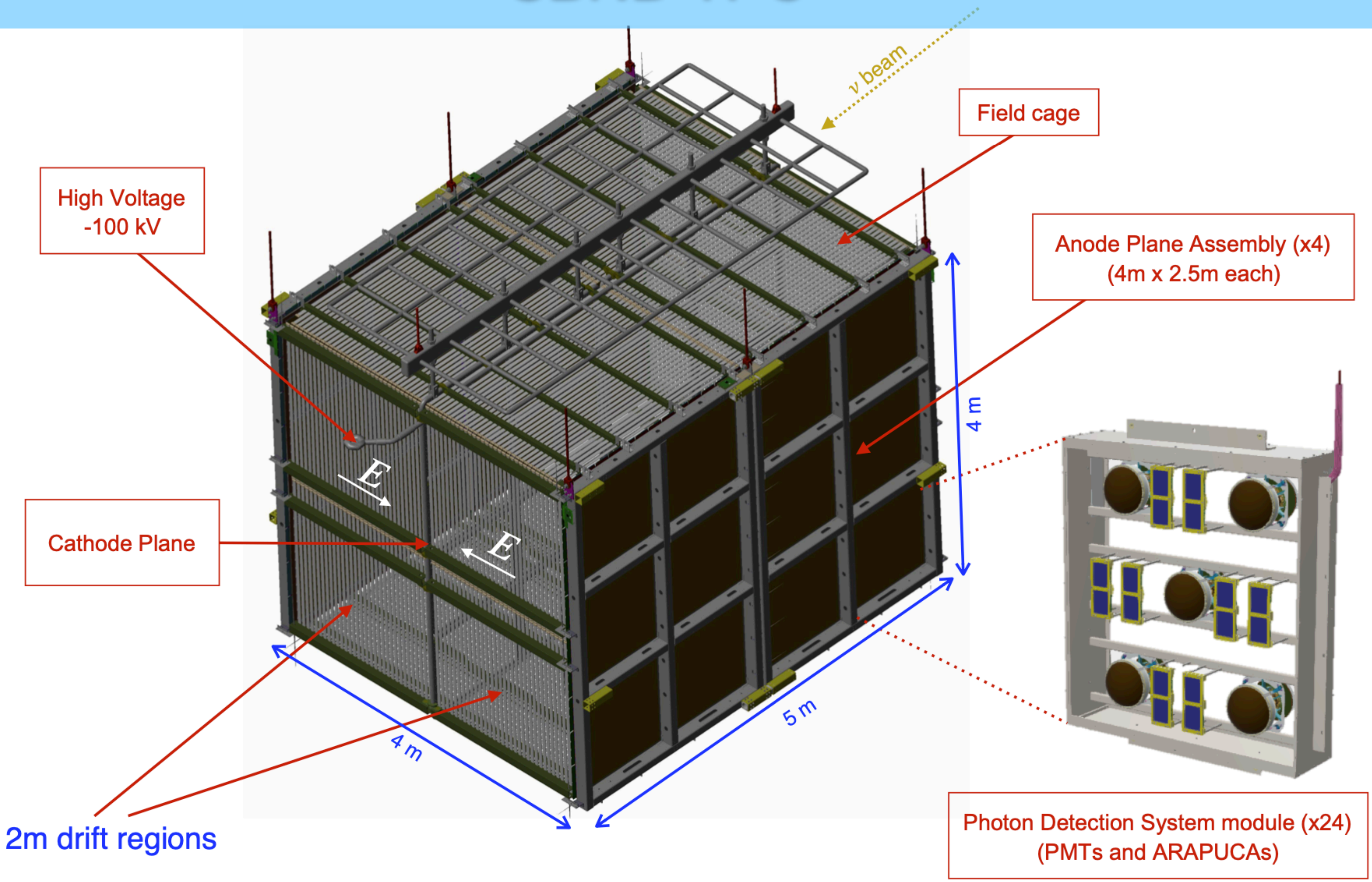
✦ Goals of the SBN program:

- Search for eV-scale sterile neutrinos
- Study of neutrino-argon interactions at the GeV energy scale
- Search for new/rare physics processes in the neutrino sector and beyond
- Advancement of the LArTPC detector technology



SBN Proposal: [arXiv:1503.01520]()

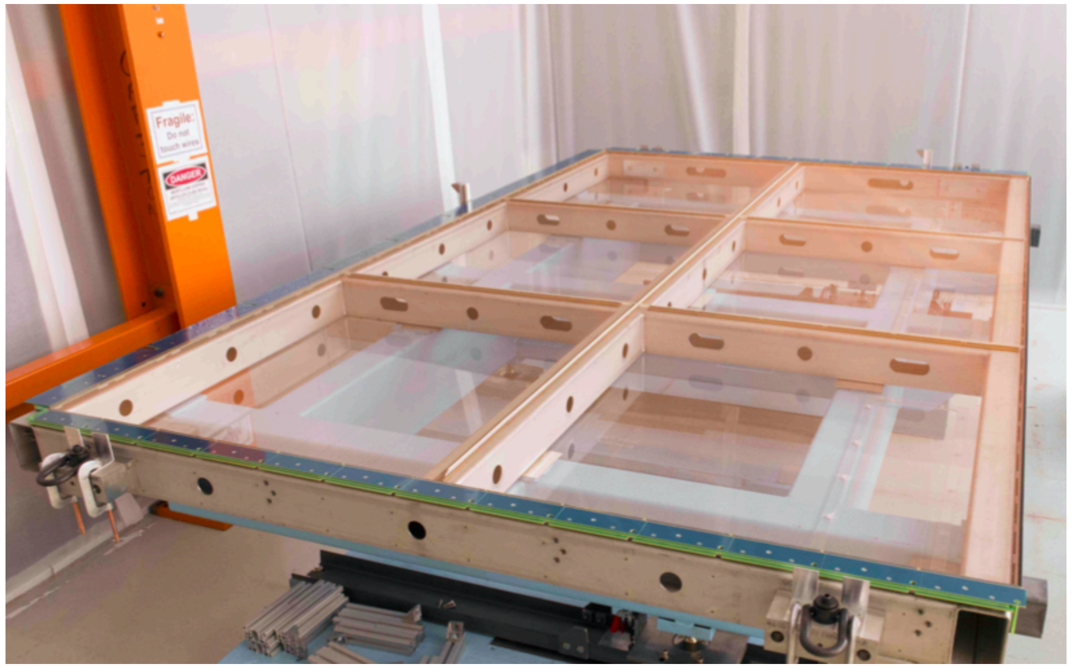
SBND TPC



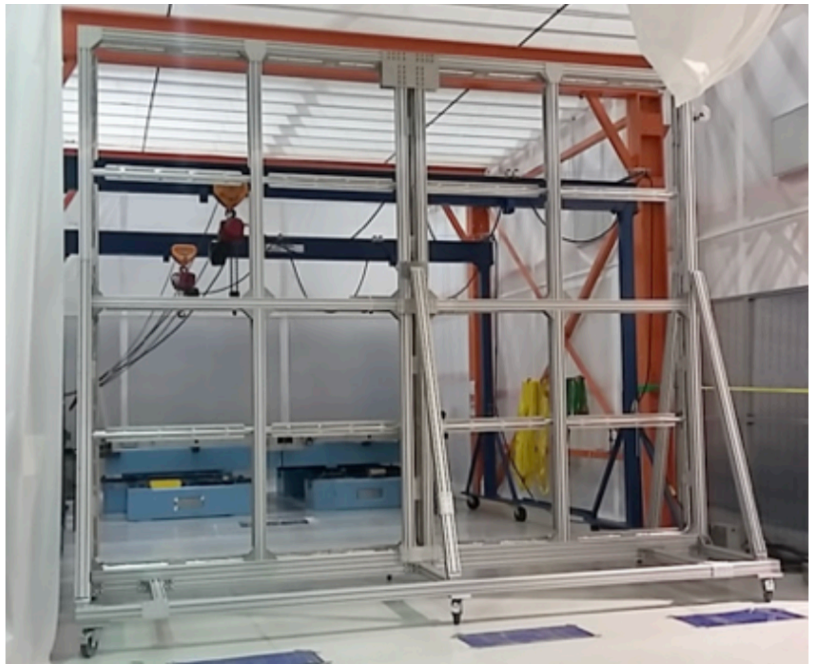
- 2 TPCs with 2 m drift length
- 1.28 ms drift time at 500V/cm
- 3 wire planes (11264 wires):
  0, ∓60 deg,
  3mm wire pitch
- Cold analog and digital electronics

- Photon Detection System (PDS)
  120 8” PMTs (96 coated with TPB)
  192 X-ARAPUCA modules
  TPB coated reflector foils on the cathode
- Full CRT (cosmic ray tagger) coverage

SBND Assembly and Installation



Anode Plane (APA)



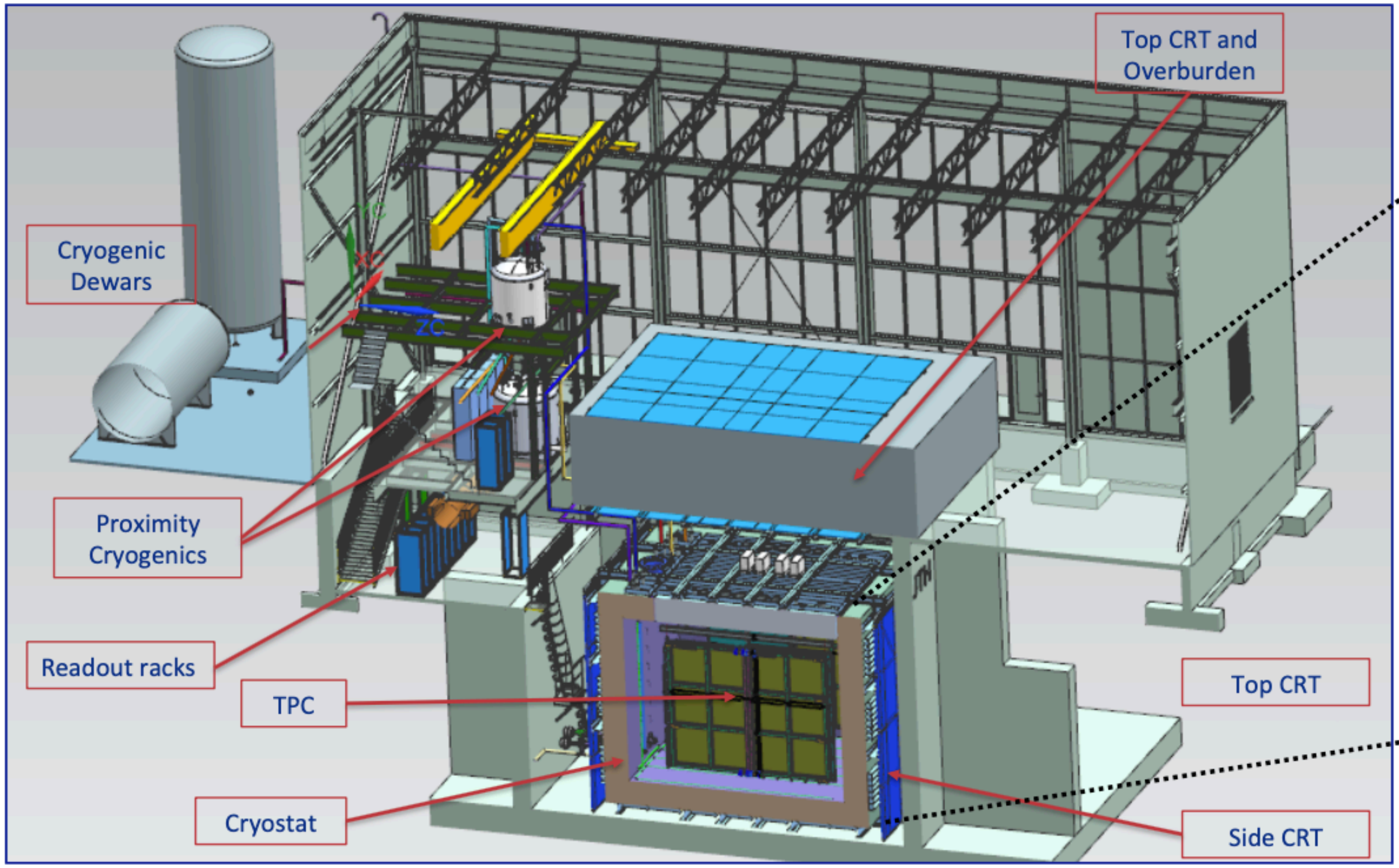
Cathode Plane (CPA)

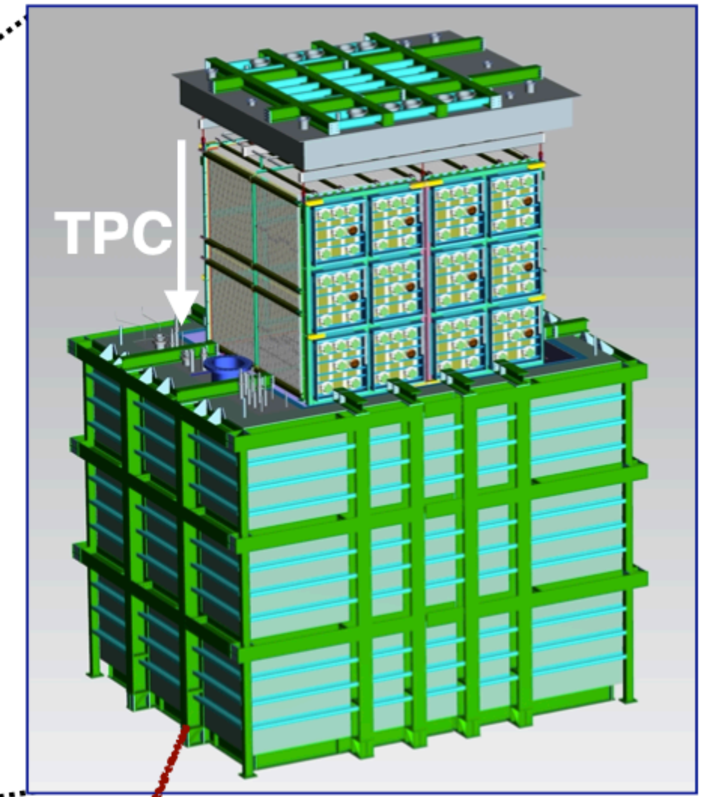
Cryogenic Installation

The Assembly Transport Frame (ATF) ready to assemble TPC components

Warm Cryostat

SBND Assembly and Installation



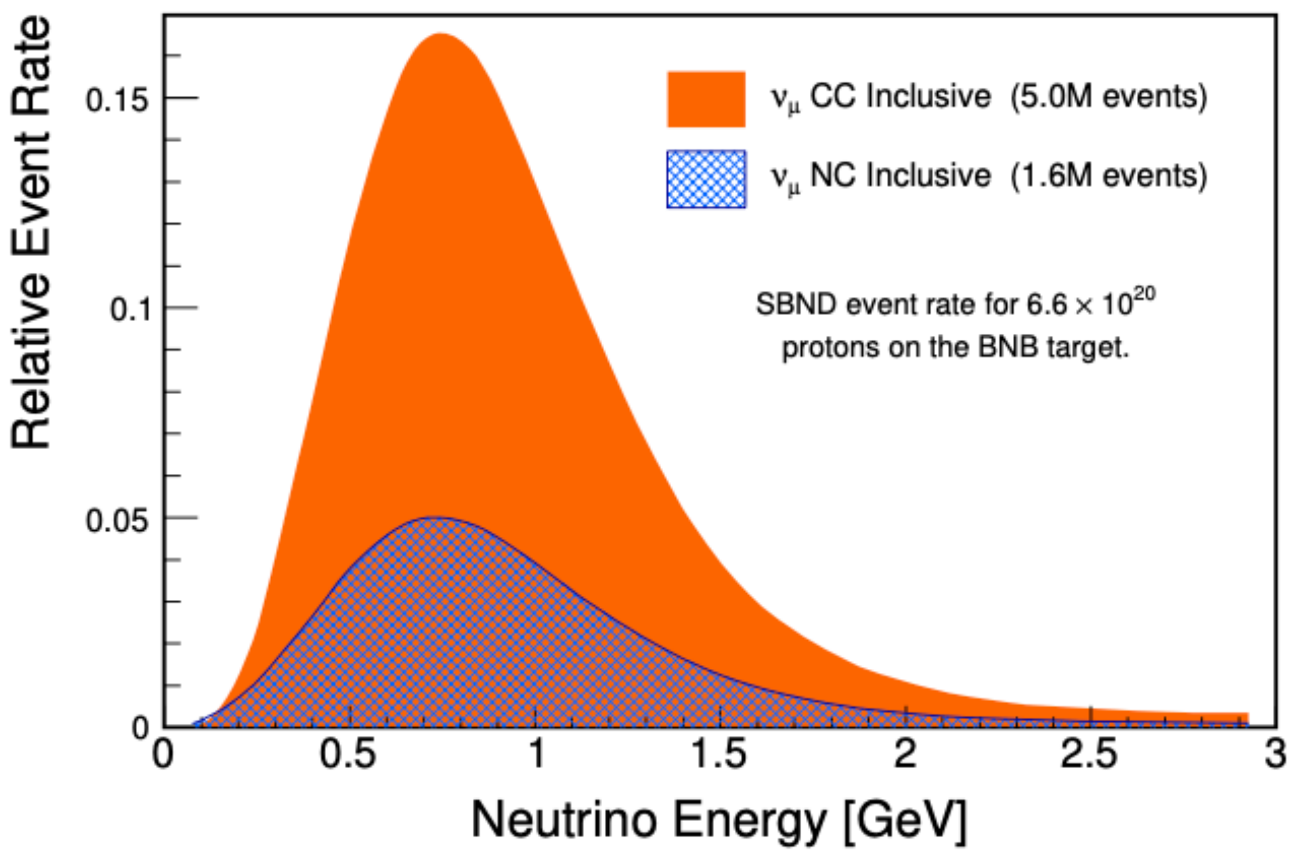


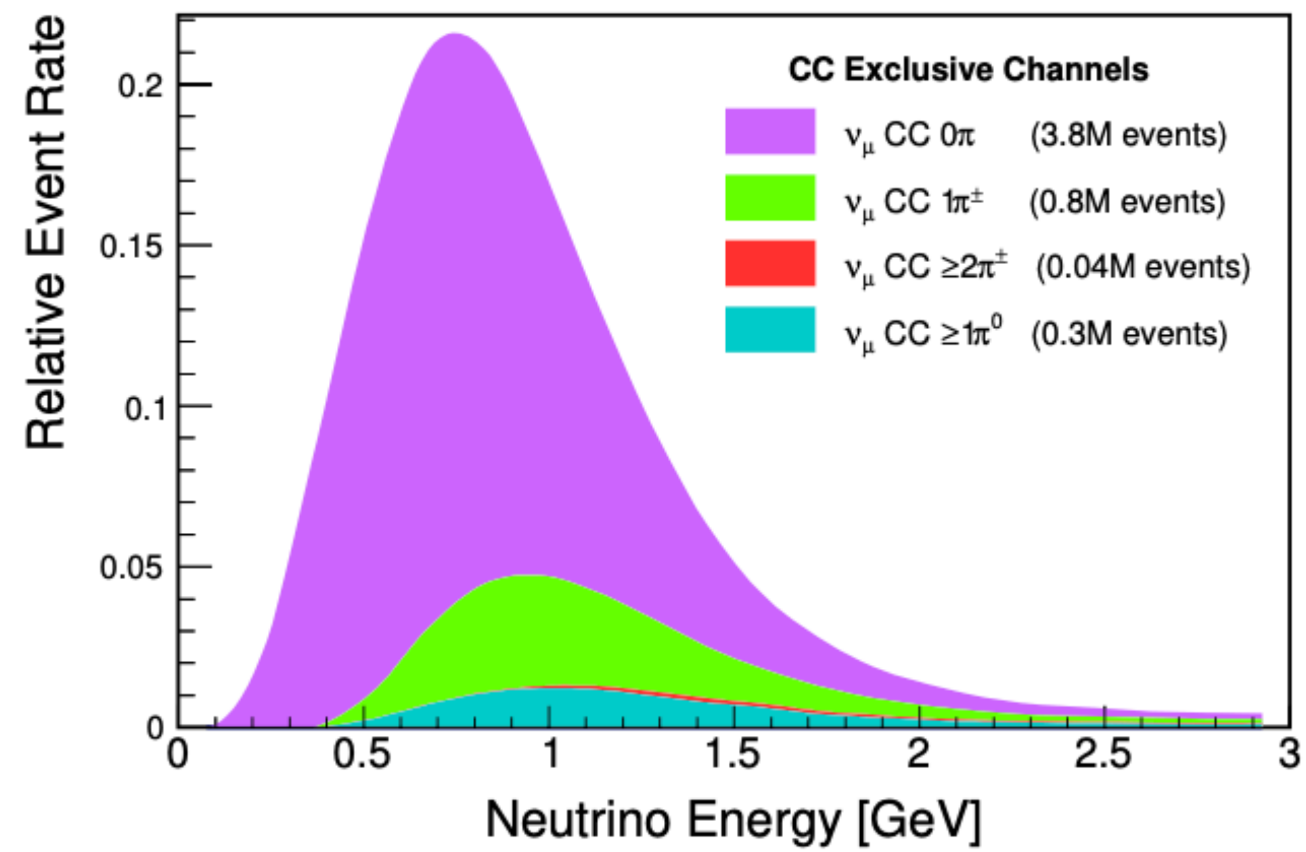
Membrane cryostat constructed inside an outer warm steel structure, with the TPC supported from the cryostat top.

✦ Neutrino-Nucleus Scattering Physics

- SBND will collect world's largest sample of neutrino interactions on argon.
  - ~7 million ν_μ interactions
  - ~50,000 ν_e interactions

Corresponds to 6.6x10^{20} protons-on-target (delivered in approximately 3 years)





SBND Physics

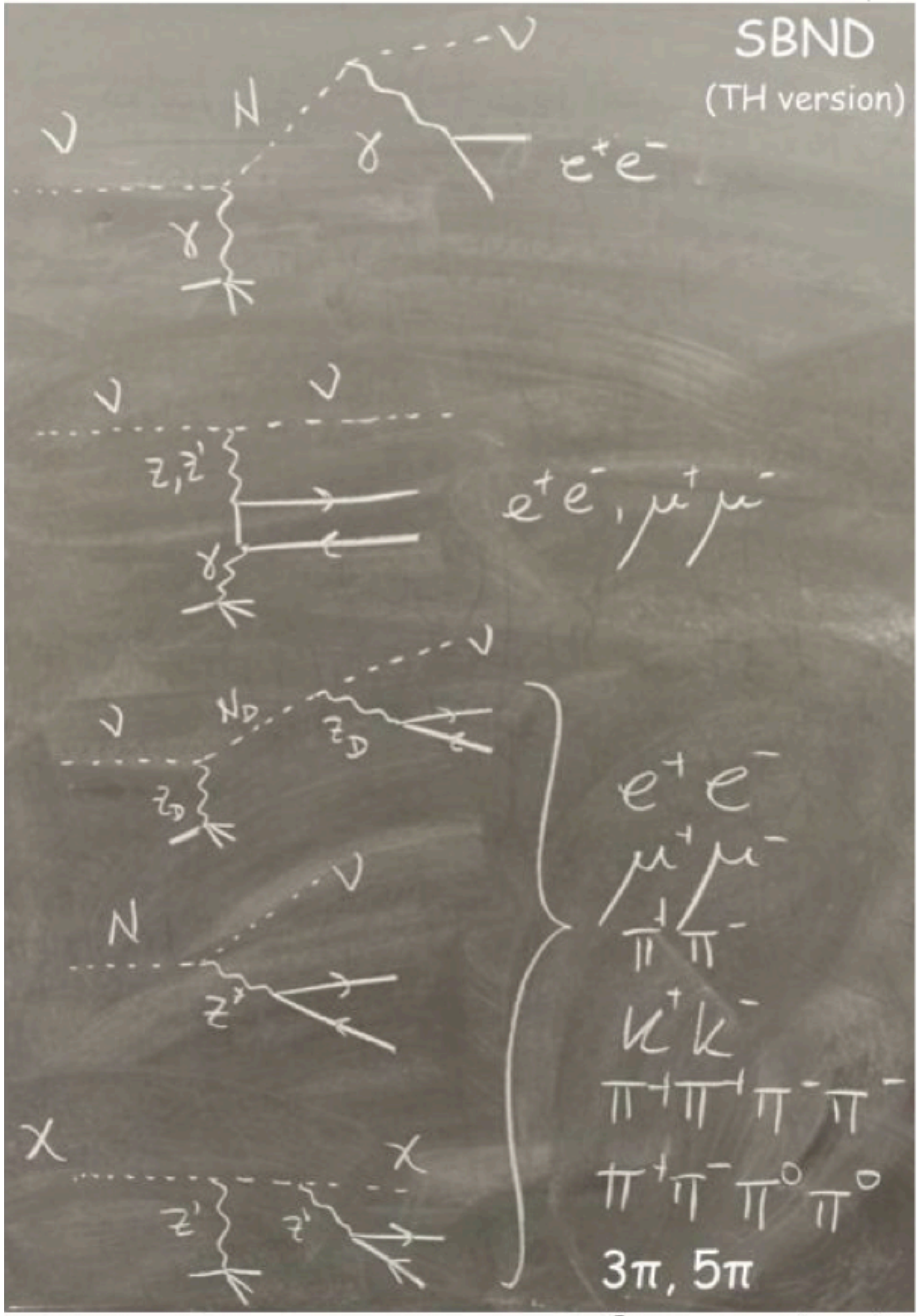
✦ Beyond the Standard Model Physics

- LArTPC capabilities combined with the proximity to the neutrino source makes SBND potentially sensitive to a vast range of BSM physics searches.

  - New states produced in the beam target (dark matter, heavy neutrinos, millicharged particles, …)

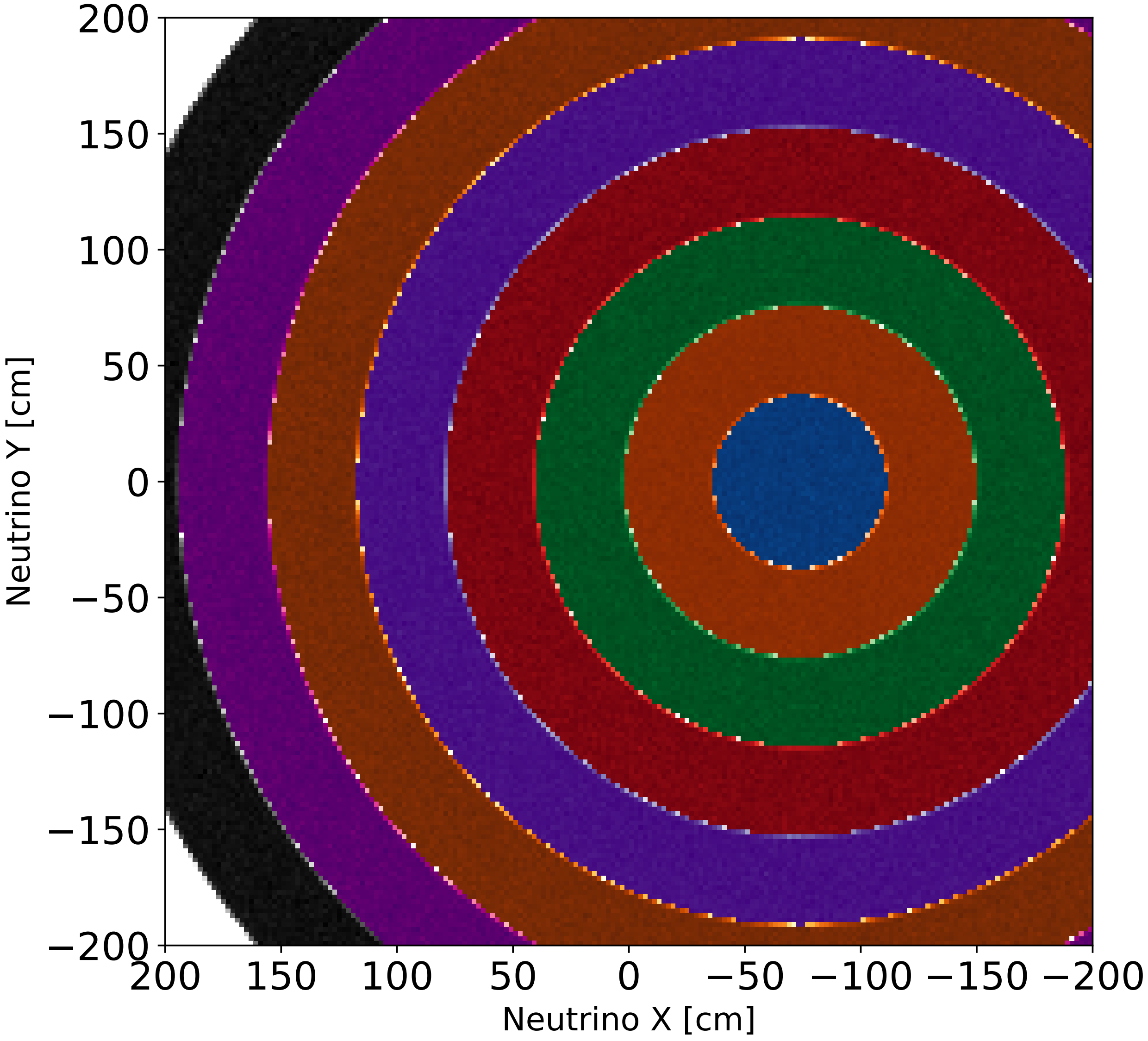
  - Modifications to neutrino oscillations (large extra dimensions, decaying sterile neutrinos, …)

A range of new physics opportunities at SBN are discussed in:
[P. A. Machado, O. Palamara, D. W. Schmitz, arXiv:1903.04608]()



Courtesy of P. Machado

SBND-PRISM



Neutrino Y [cm]
200
150
100
50
0
−50
−100
−150
−200
200
150
100
50
0
−50
−100
−150
−200
Neutrino X [cm]

NuPRISM and DUNE-PRISM

✦ **Neutrino beam "off-axis" effect**: as one moves away from the neutrino beam axis, the observed neutrino energy spectrum narrows and peaks at a lower energy. By measuring neutrino interactions across a range of off-axis angles one would control the neutrino interaction uncertainty in the oscillation analysis.

NuPRISM and DUNE-PRISM

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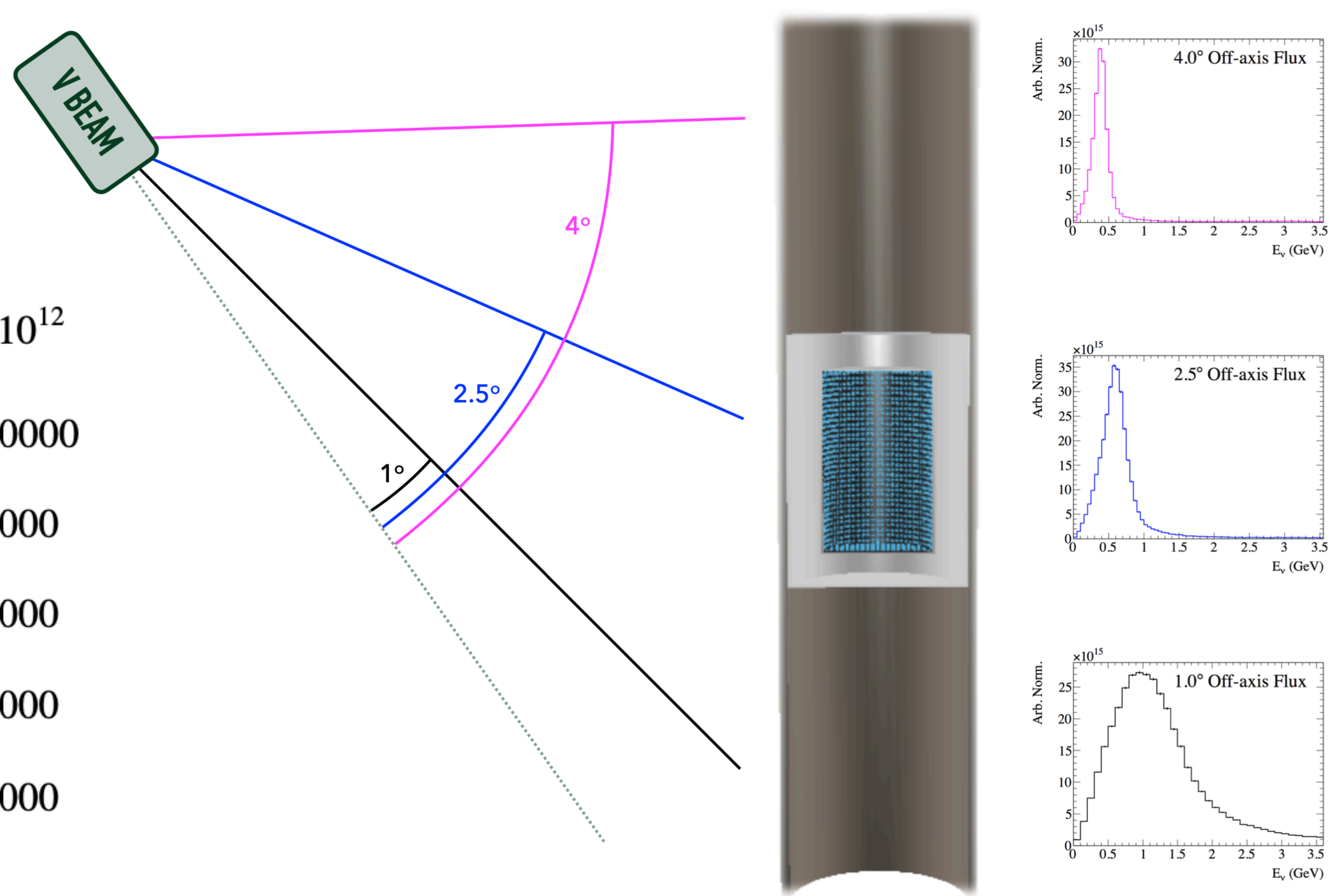
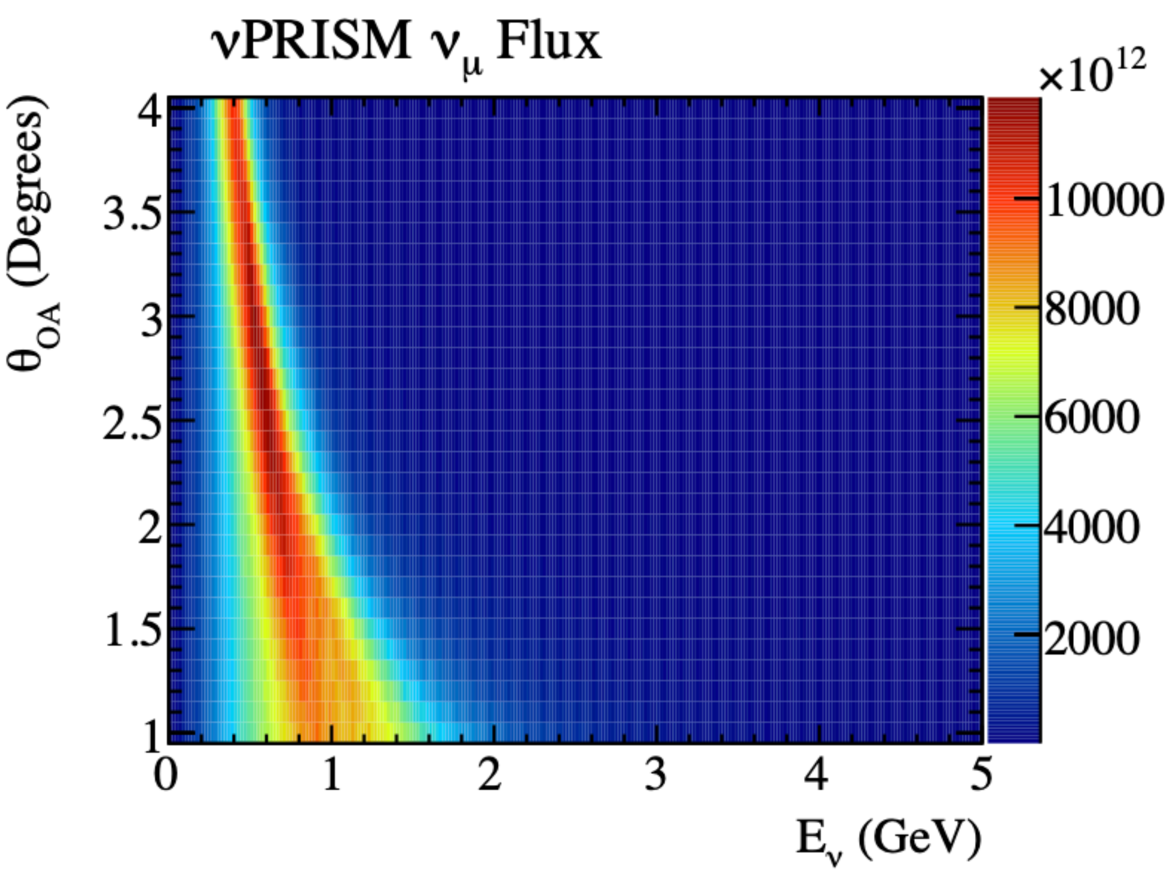
✦ NuPRISM

- Water Cherenkov detector moves through a cylindrical chamber
- 1 km downstream of the neutrino target
- Scans upto 4 degrees from the neutrino beam axis

[nuPRISM Collaboration], arXiv:1412.3086 [physics.ins-det]





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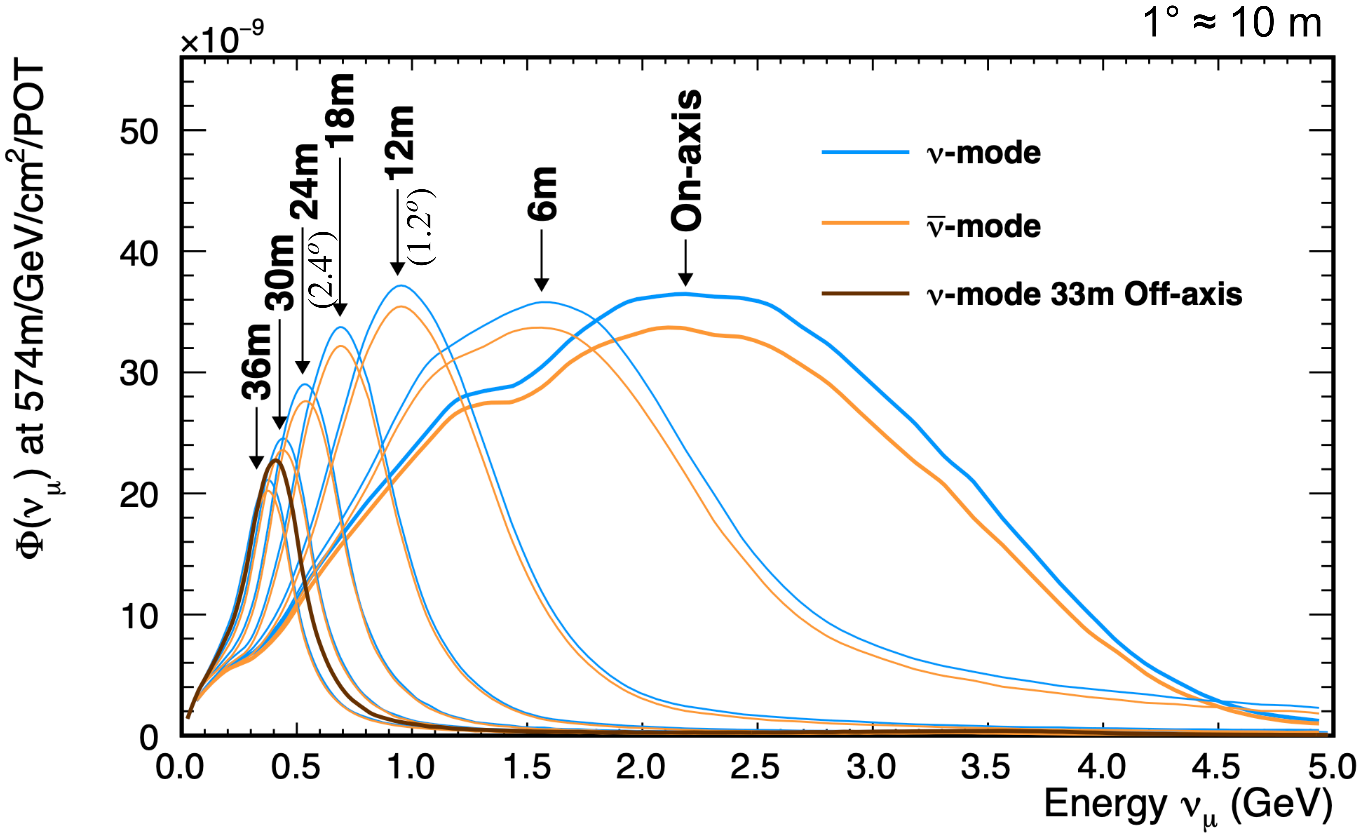
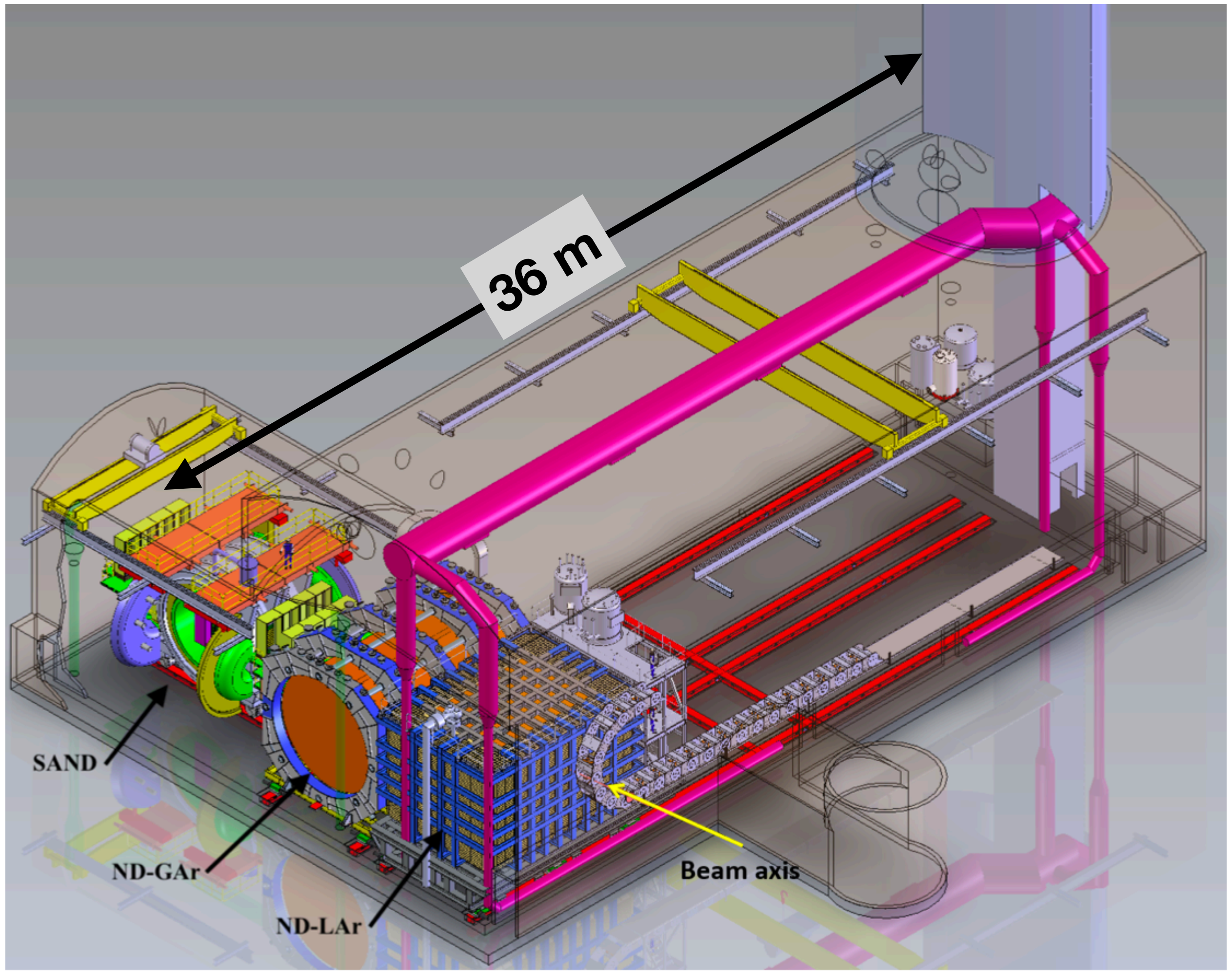
✦ DUNE-PRISM

[DUNE Collaboration], arXiv:2103.13910 [physics.ins-det]

- Movable LAr and GAr modules
- 574 m downstream of the neutrino target
- Scans upto 3.2 degrees from the neutrino beam axis



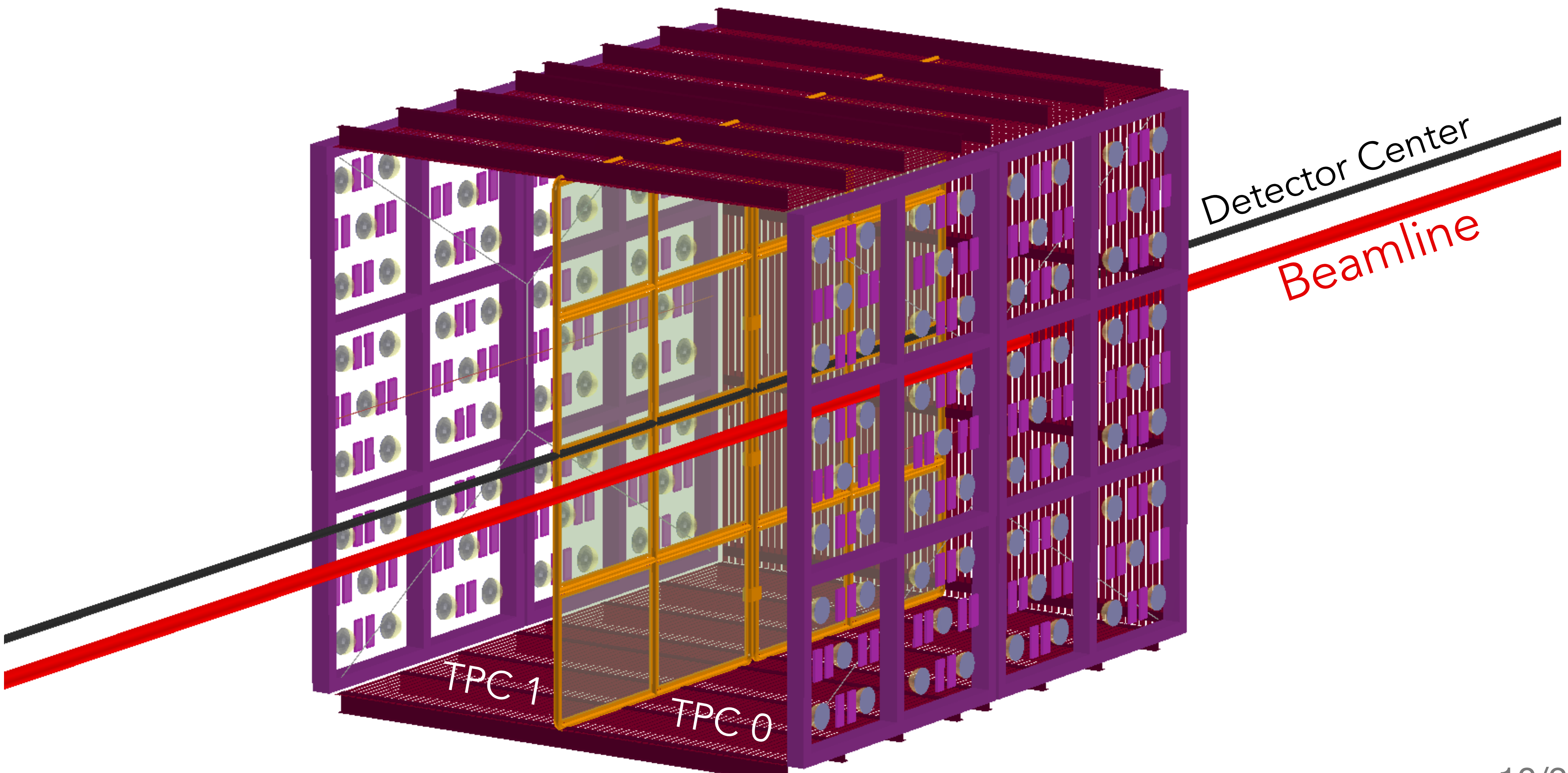


SBND-PRISM

✦ **SBND-PRISM**

- 112 ton LAr detector, 4m x 4m x 5m dimension
- 110m from the neutrino target
- 2 LArTPCs: TPC 0, TPC1

- Detector is ~74 cm off the beam axis



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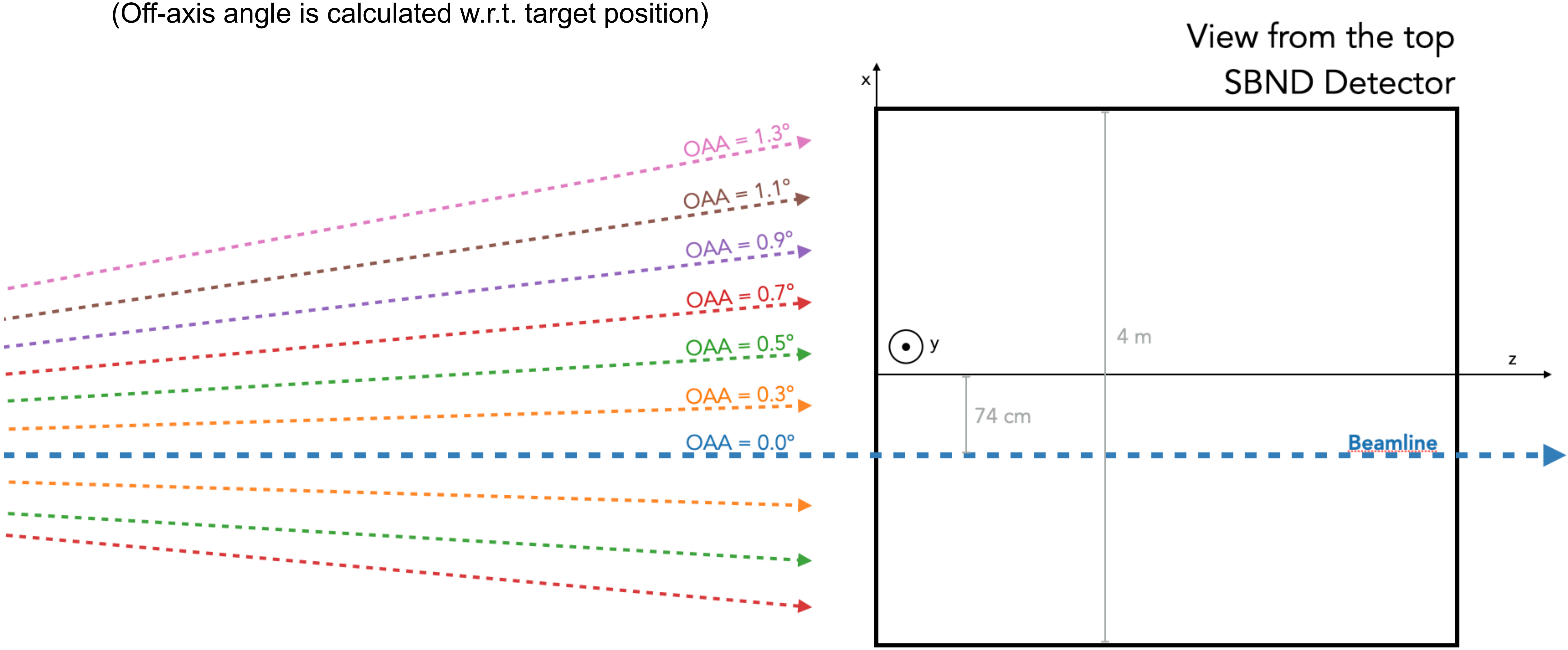
- Scans upto ~ 1.3 degree off-axis angles (OAAs)
  (Off-axis angle is calculated w.r.t. target position)

DUNE: 1° ≈ 10 m
SBND: 1° ≈ 2 m



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- The detector can be divided in several off-axis slices:

OAA ∈ [0.0°, 0.2°)

OAA ∈ [0.2°, 0.4°)

OAA ∈ [0.4°, 0.6°)

OAA ∈ [0.6°, 0.8°)

OAA ∈ [0.8°, 1.0°)

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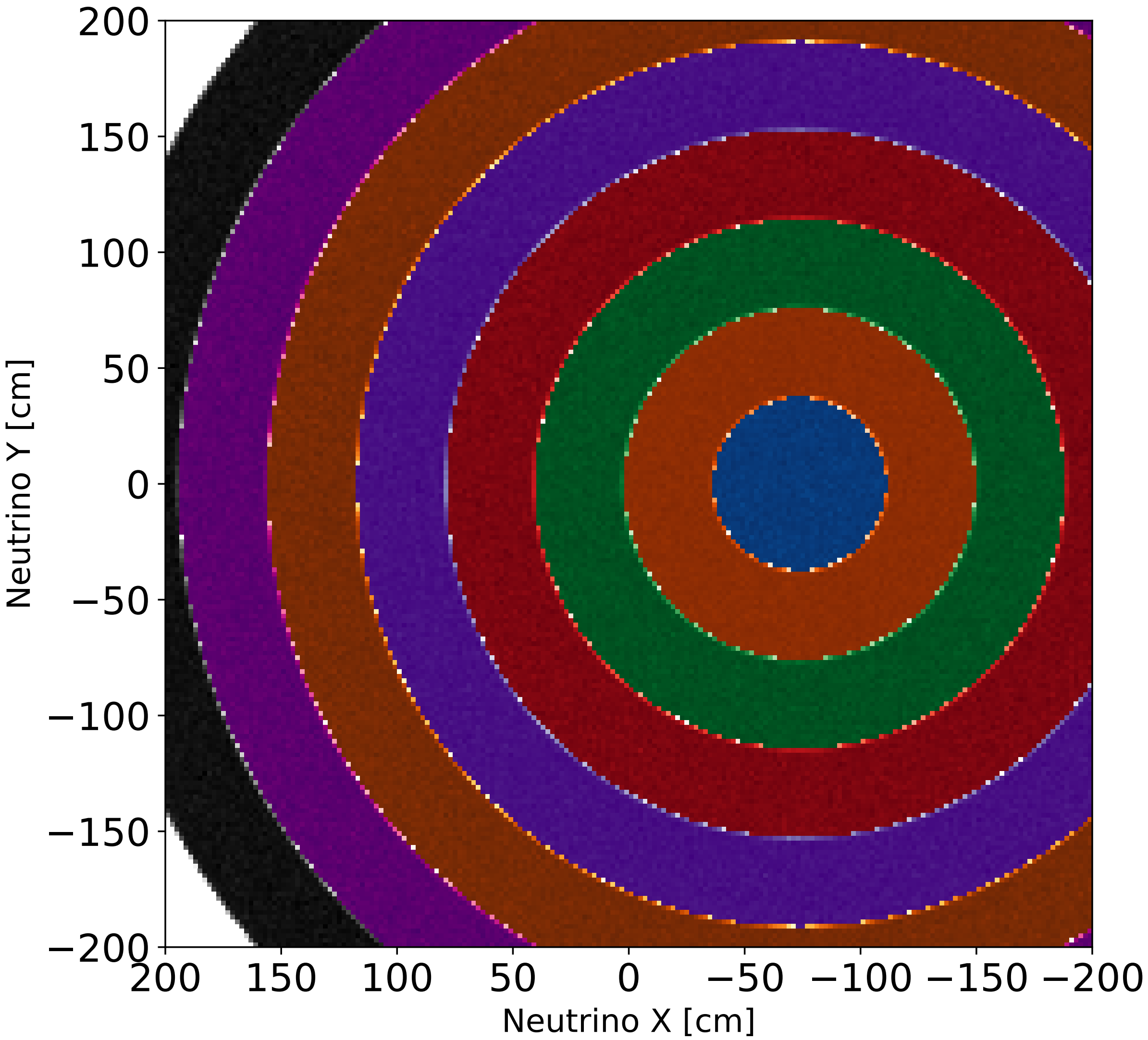


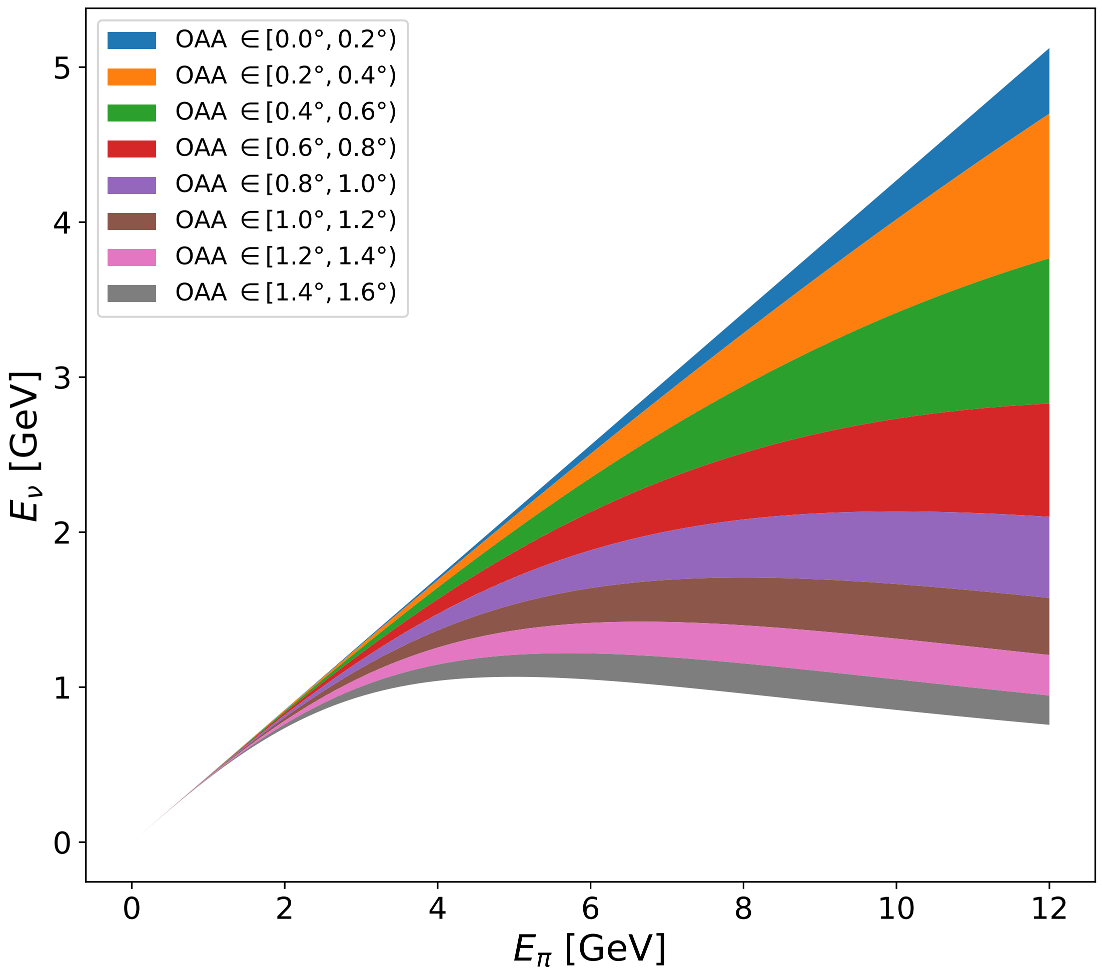
SBND-PRISM: ν_μ Flux

▪ ν_μ Energy Distribution

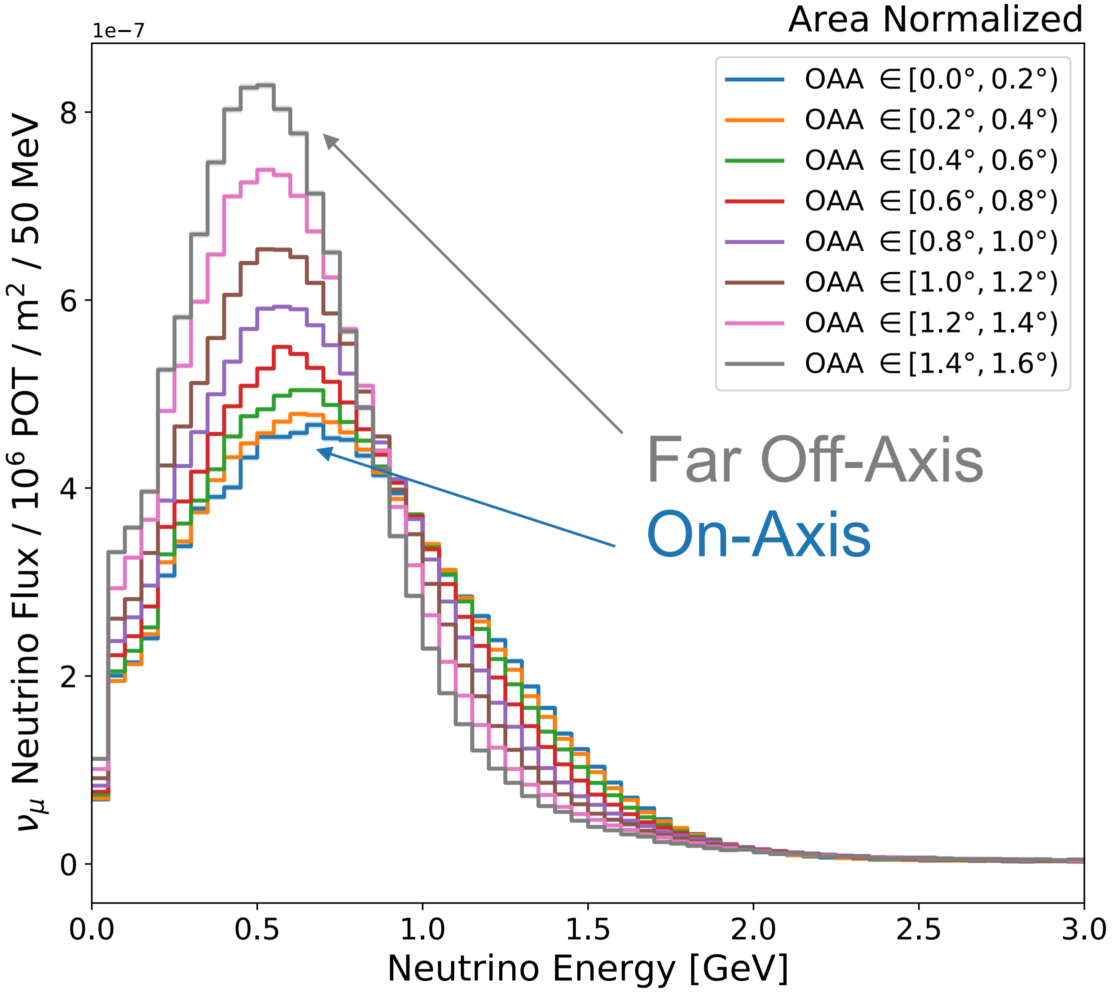
- ν_μ come predominately from the two-body decay, less angular spread, flux changes rapidly with respect to the beam axis.
- With the OAA, the observed neutrino energy spectrum narrows and peaks at a lower energy.

$$\pi^+ \to \nu_\mu + \mu^+$$
$$K^+ \to \nu_\mu + \mu^+$$

Mean neutrino energy



ν_μ flux in each of the OAA regions



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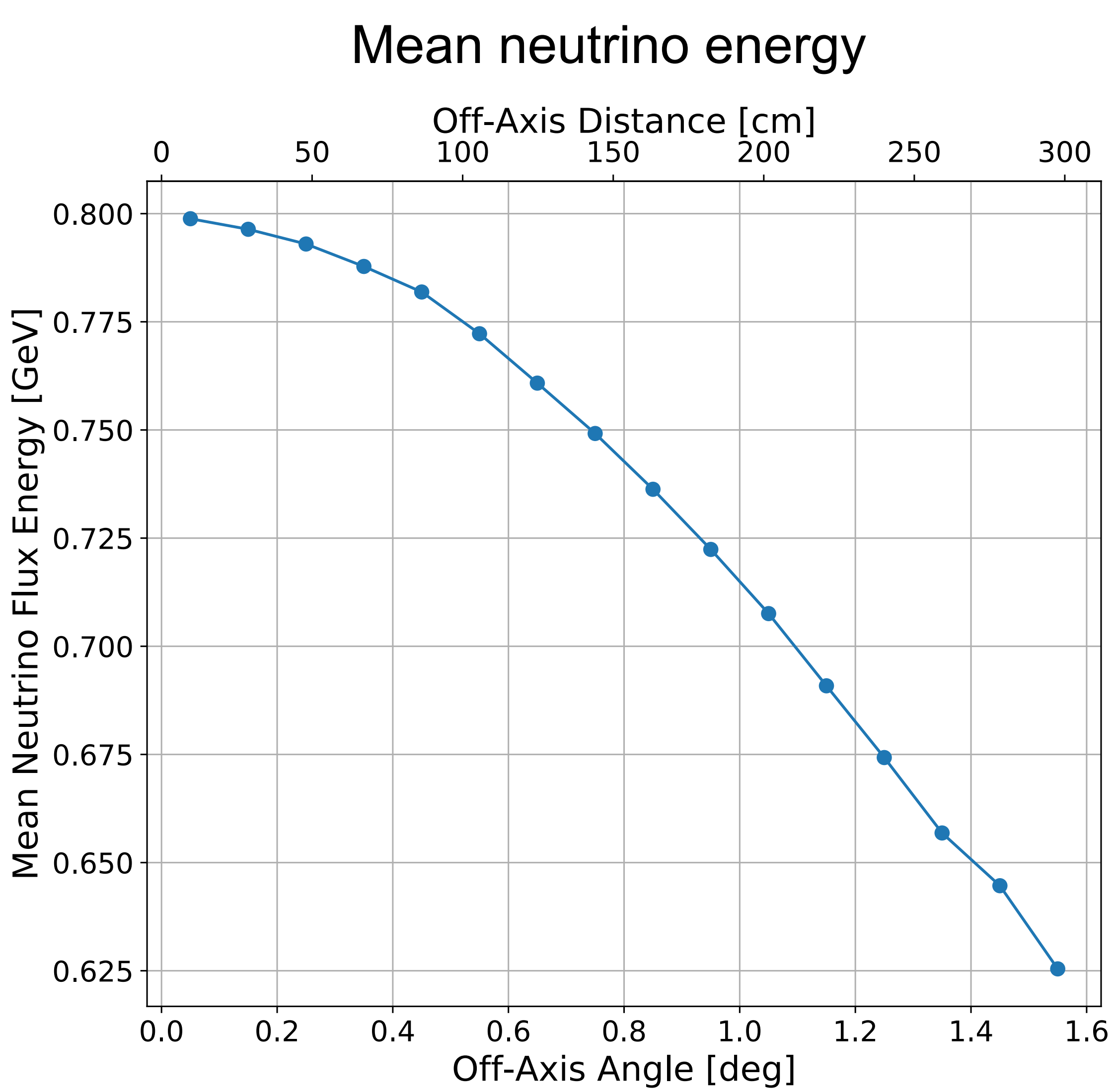
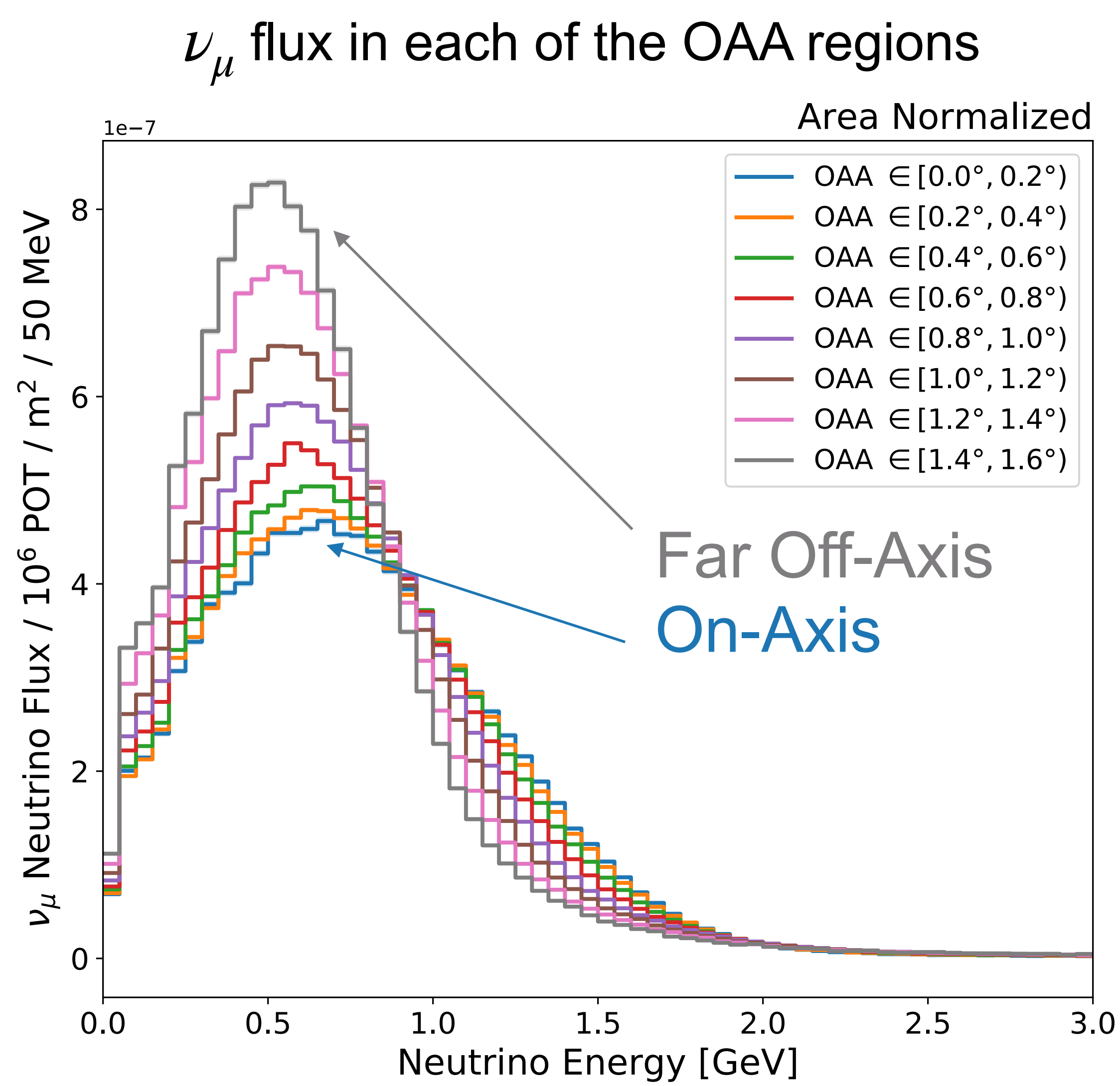




SBND-PRISM: ν_μ to ν_e Differences

■ ν_μ to ν_e Events Distributions

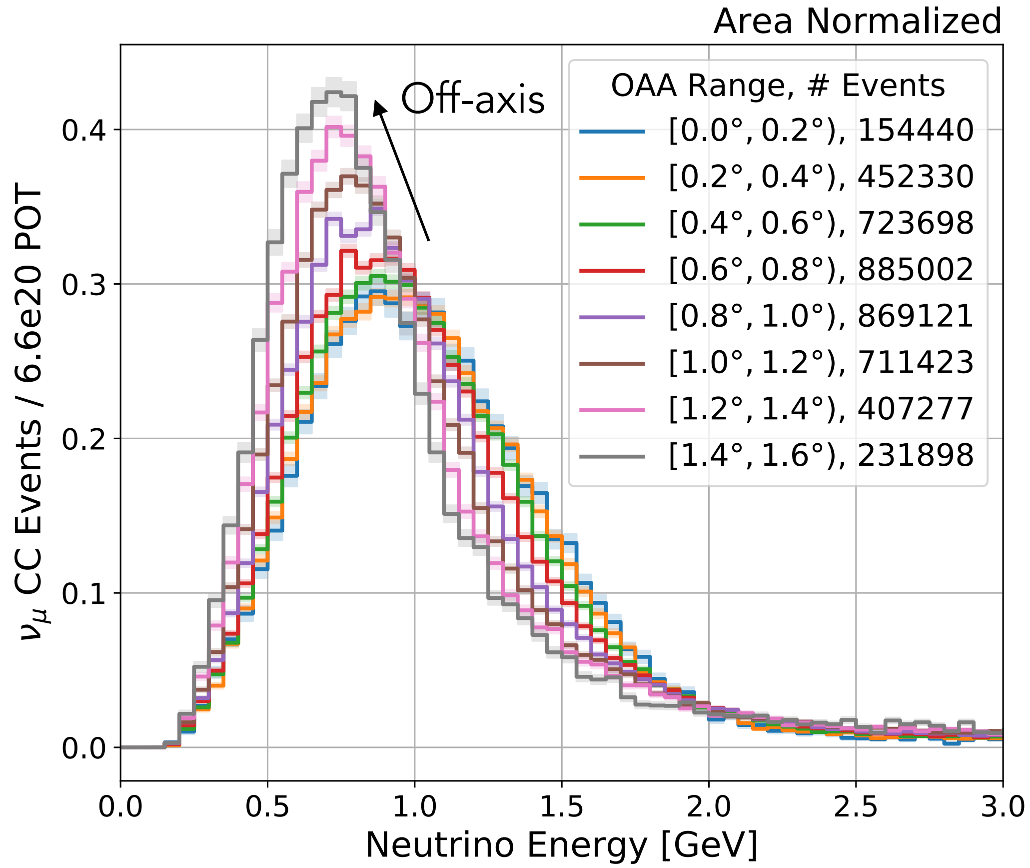
- Unlike ν_μ, ν_e come predominately from the three-body decay. For the same parent energy, the ν_e flux has a larger angular spread than that of ν_μ, and does not follow the same "off-axis" effect as ν_μ.

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$K^+ \rightarrow \nu_\mu + \mu^+$$

$$\mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+$$
$$K^+ \rightarrow \nu_e + e^+ + \pi^0$$
$$K_L^0 \rightarrow \nu_e + e^+ + \pi^-$$

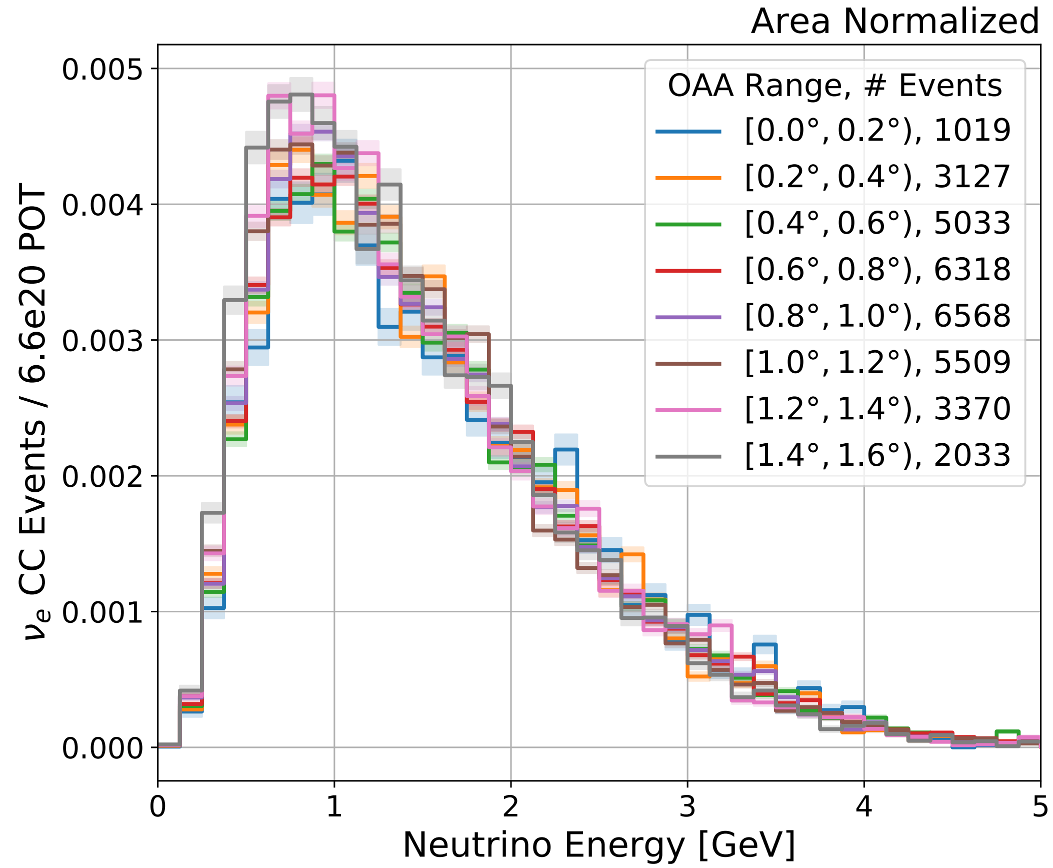
ν_μ CC Events

higher off-axis angle → lower mean energy



ν_e CC Events

higher off-axis angle → ~same mean energy



- Note high event statistics in all off-axis regions

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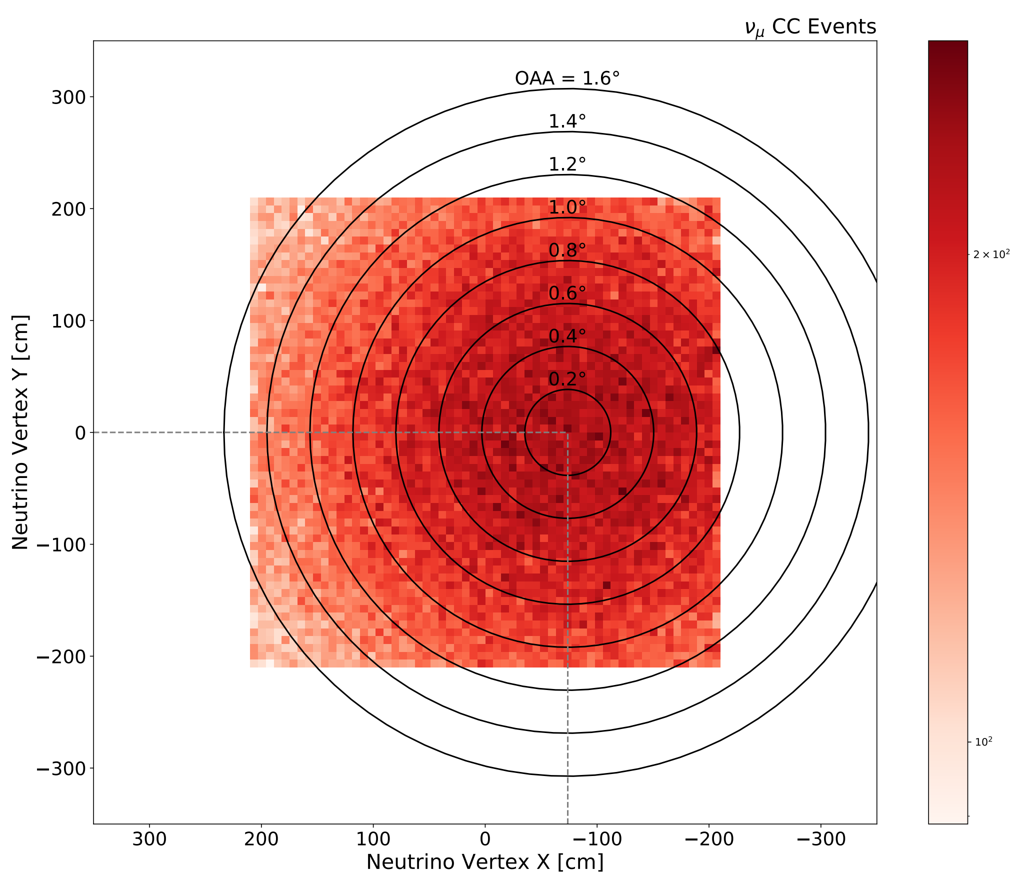
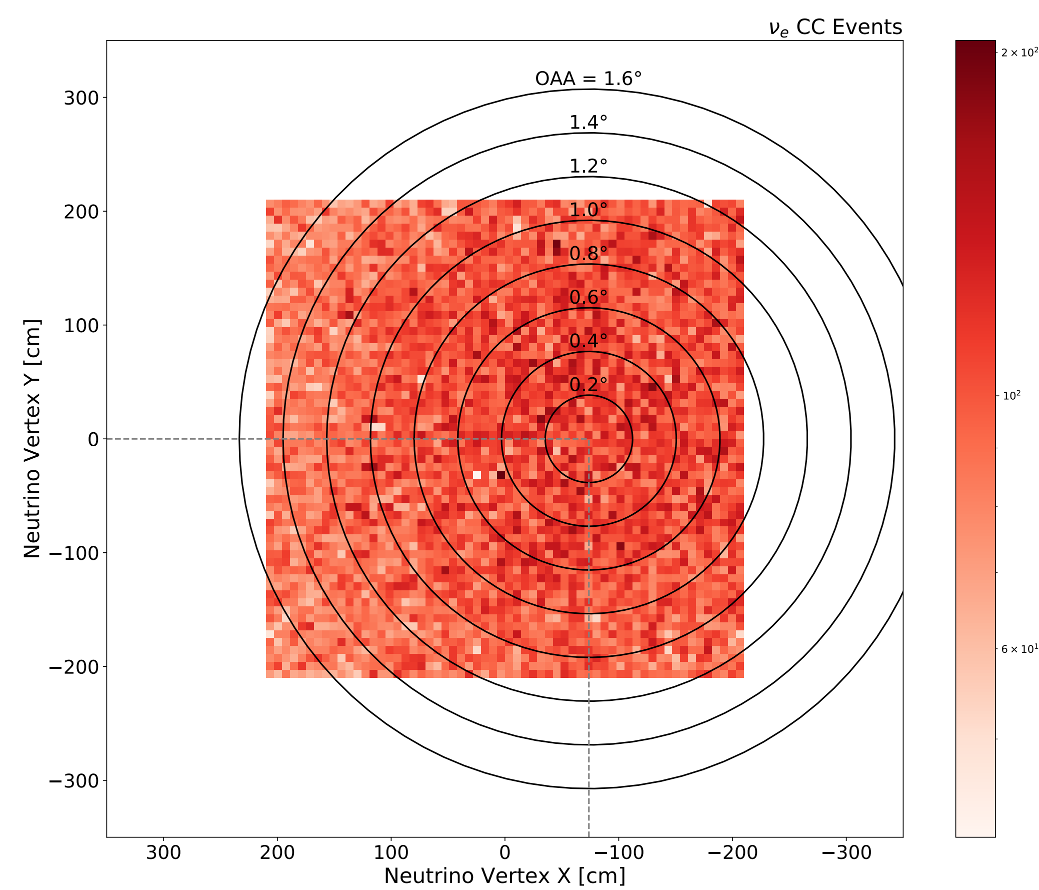
ν_μ CC Events

peak coincides with the on-axis position



ν_e CC Events

distribution is almost constant



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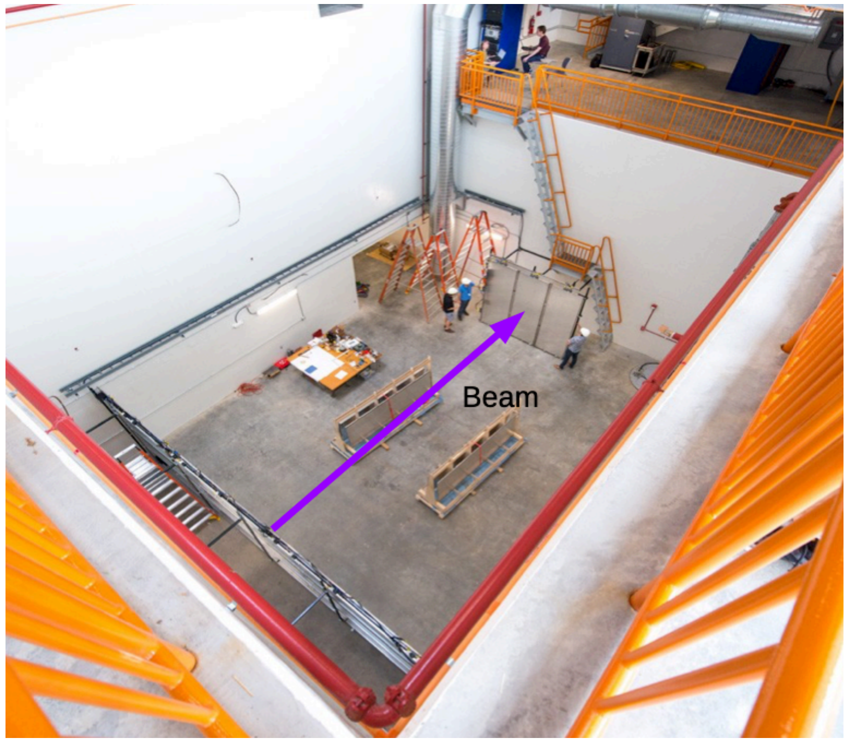
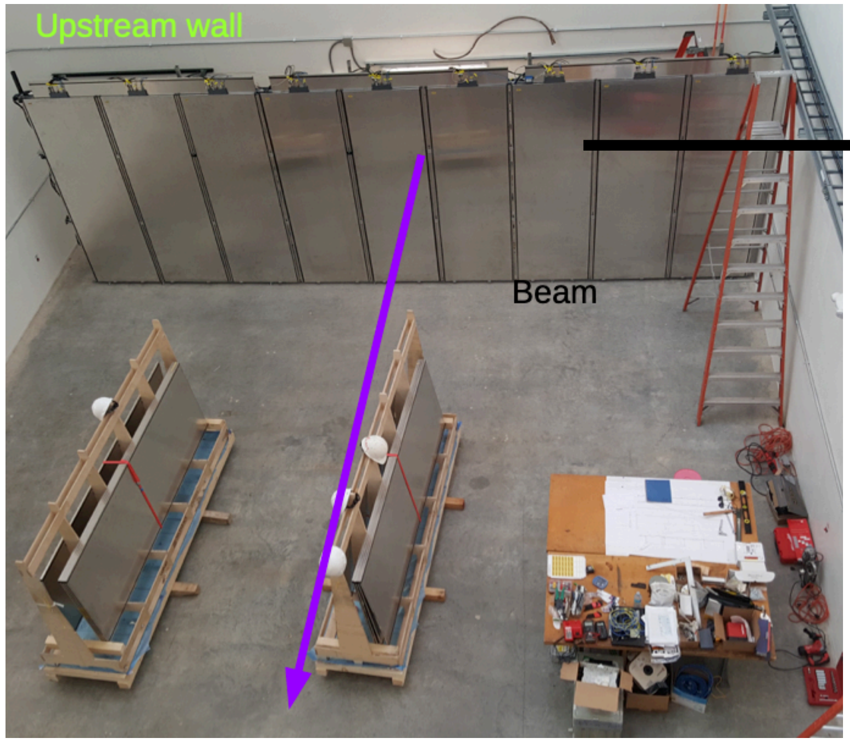
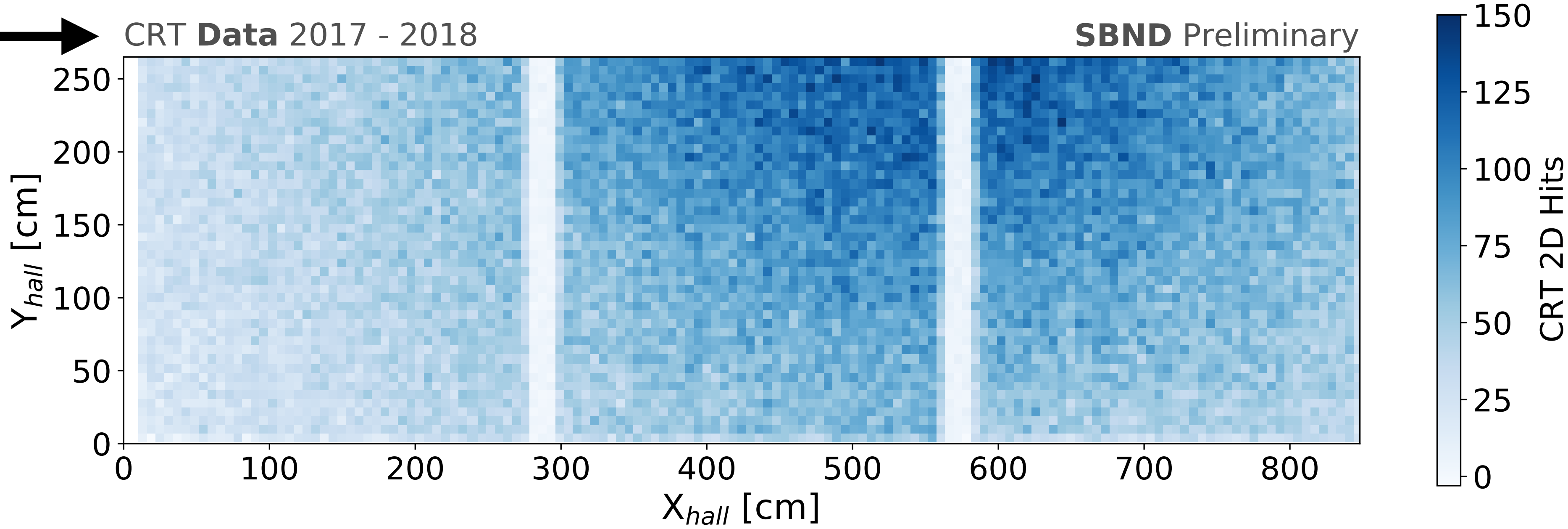
SBND-PRISM: CRT Data

■ CRT Data



- Part of the SBND cosmic ray tagger system was temporary installed in the detector hall.
- Below is a real data plot of **muons from neutrinos** interacting in the material upstream of the SBND detector hall (cosmic background subtracted).
- Data taken with the CRT shows the number of beam-induced muons decreases moving away from the beam center.



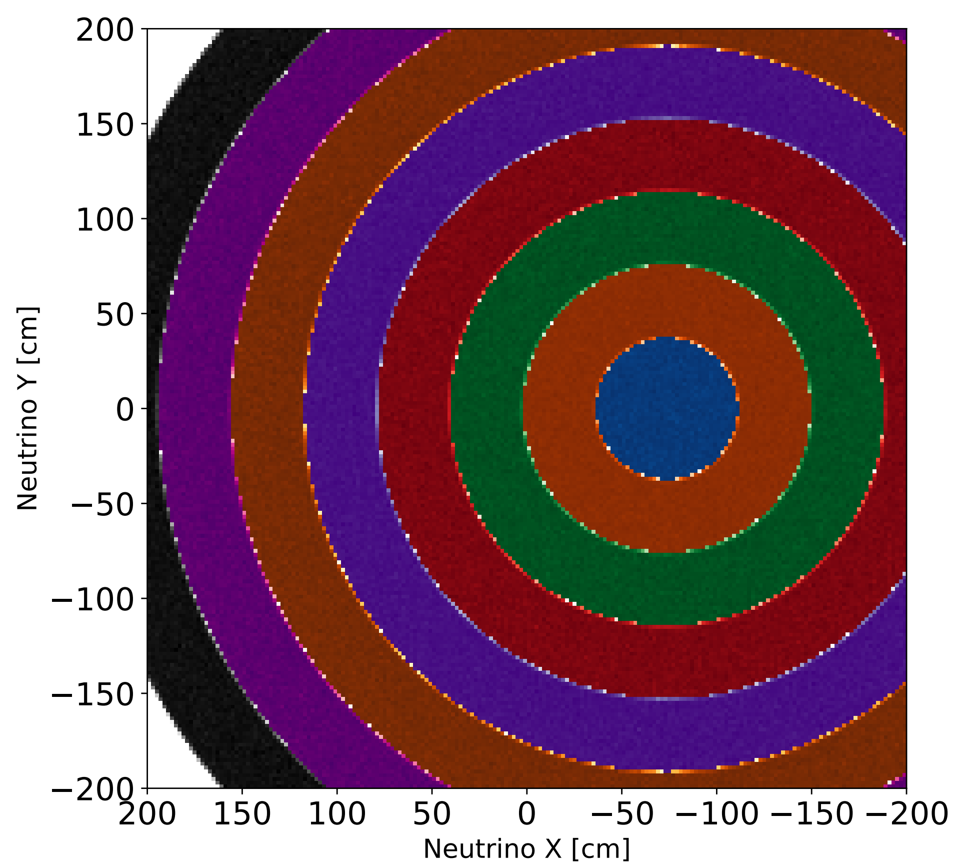


SBND-PRISM: Physics Potential

- **Exploring Physics Potential of the SBND-PRISM**

  (Some ongoing studies, feedback/ideas welcome)

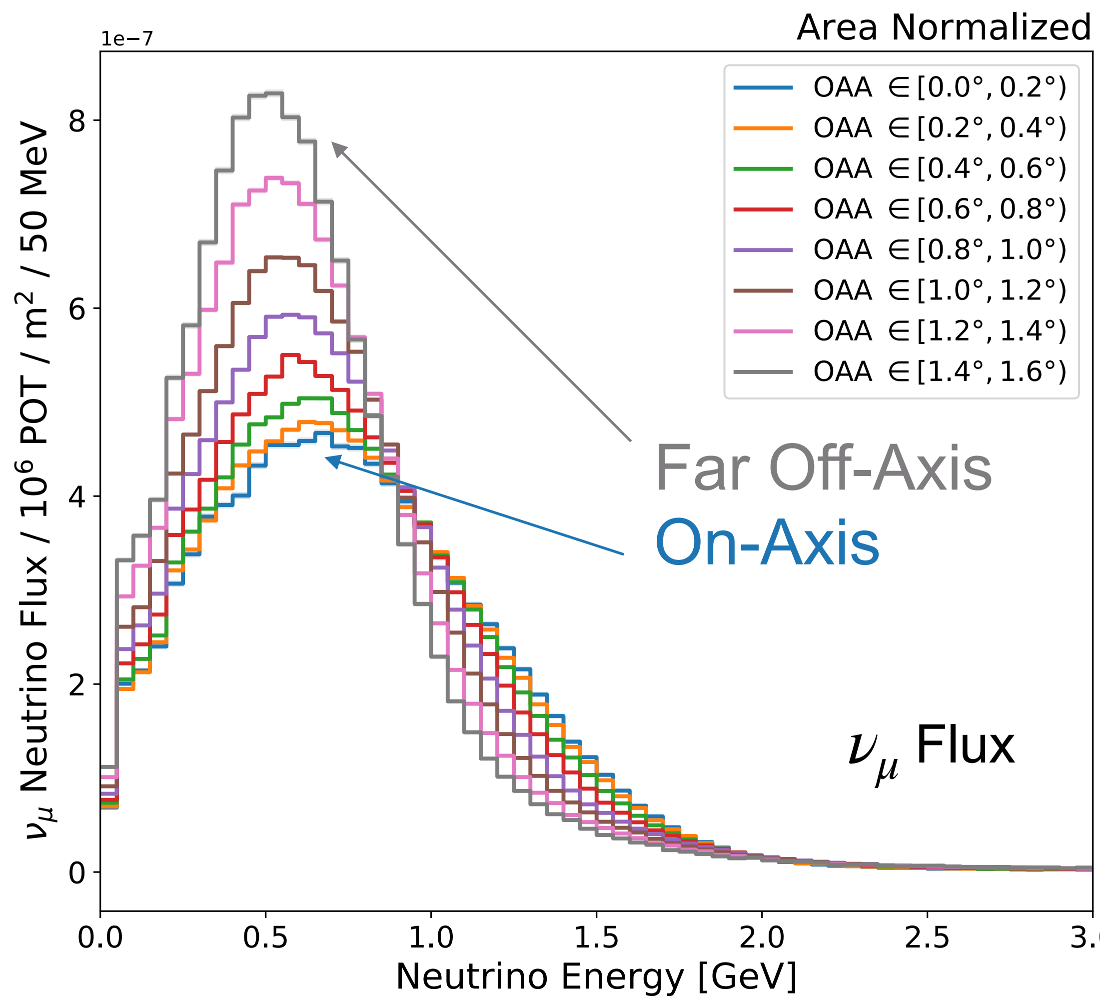
  - Neutrino-Nucleus Interactions
  - Neutrino Oscillations
  - Dark Matter Searches
  - …



SBND-PRISM: Neutrino-Nucleus Interactions

◆ Neutrino-Nucleus Interactions Physics

- **Energy dependence:**
  - By measuring neutrino interactions at different OAA, we can directly infer the energy dependence of the cross section (and various nuclear effects) spanning over nearly 200 MeV energy difference.
  - Study the relationship between neutrino energy, and lepton (and hadron) kinematics, done by measuring differential cross-section in lepton (and hadron) kinematics at different OAA.



- Need realistic neutrino interaction model to study subtle effects across the ~200 MeV difference (before we have data).

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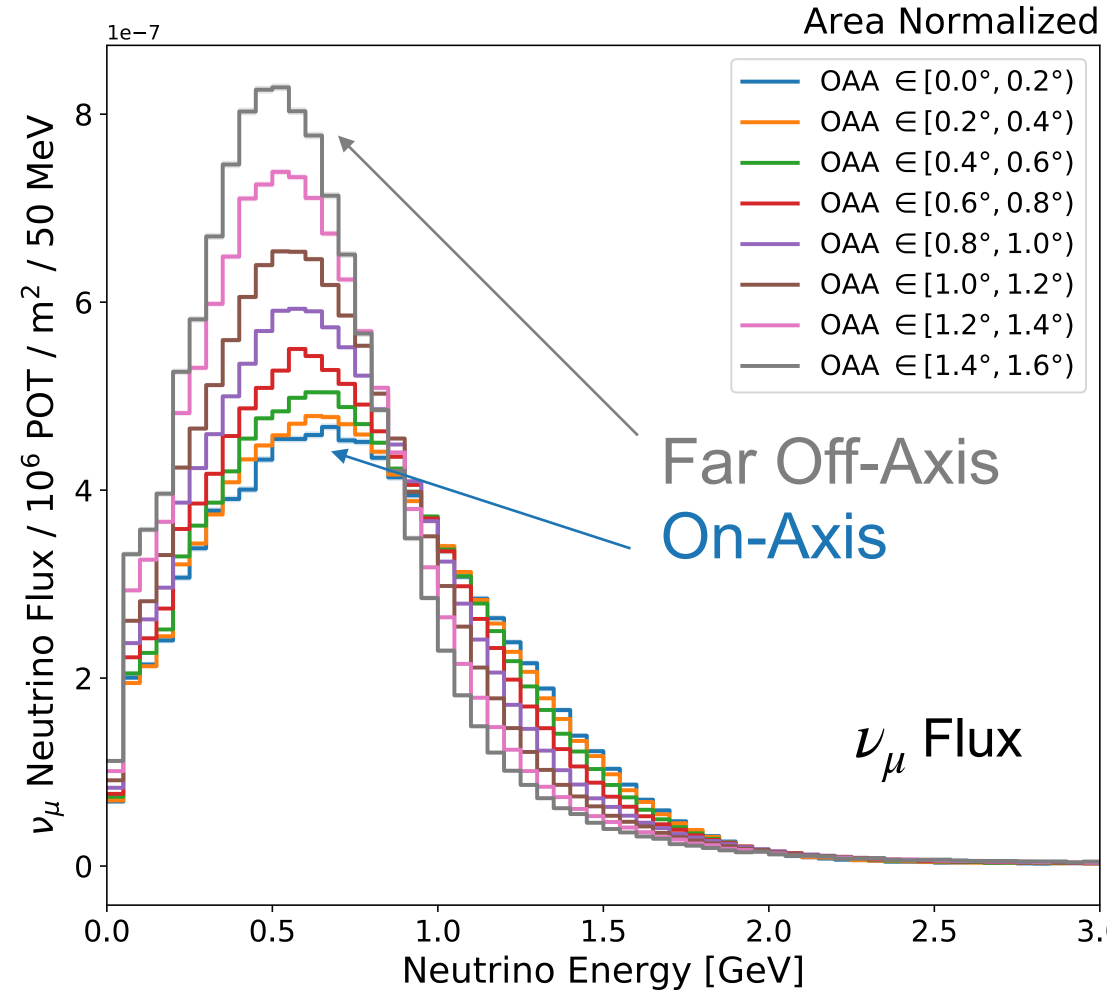
- **Disentangling nuclear physics at the "higher-energy" tail:**
  - The "higher energy" tail of the ν_μ flux shrinks as a function of the OAA. This would potentially allow us to disentangle nuclear effects that start to dominate at ~1 GeV energy, e.g. non-QE contributions (2p-2h contribution, etc.).



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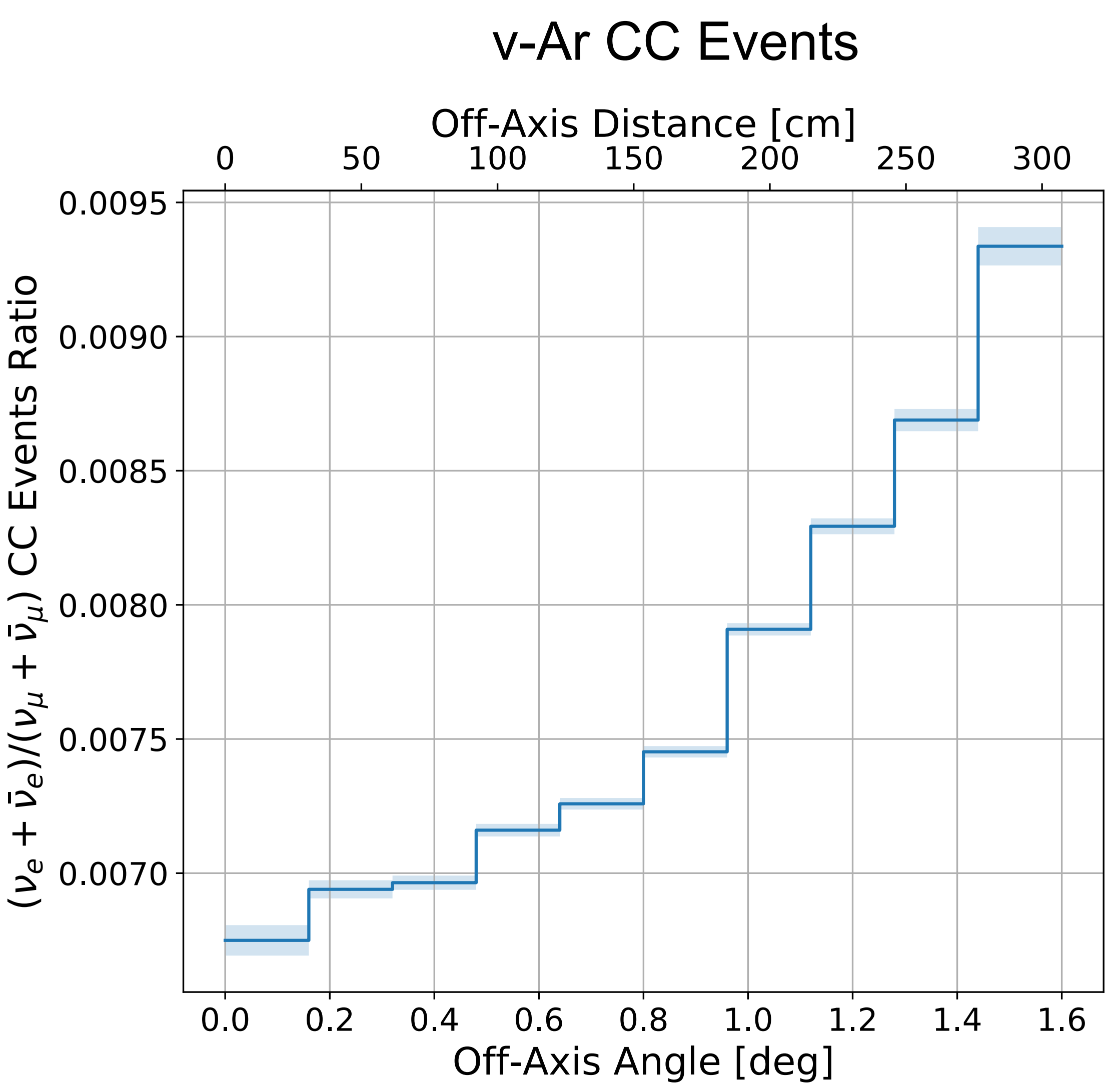
◆ Neutrino-Nucleus Interactions Physics

- **ν_μ to ν_e cross sections:**
  - Going off-axis, the increase in ν_e to ν_μ flux ratio combined with a choice of kinematics where ν_e to ν_μ differences are expected to be prominent should allow us to measure the ν_e/ν_μ cross section.
  - This would allow us to study lepton mass effects, and test Lepton Flavor Universality.
  - Note that we expect high event statistics in all off-axis regions.



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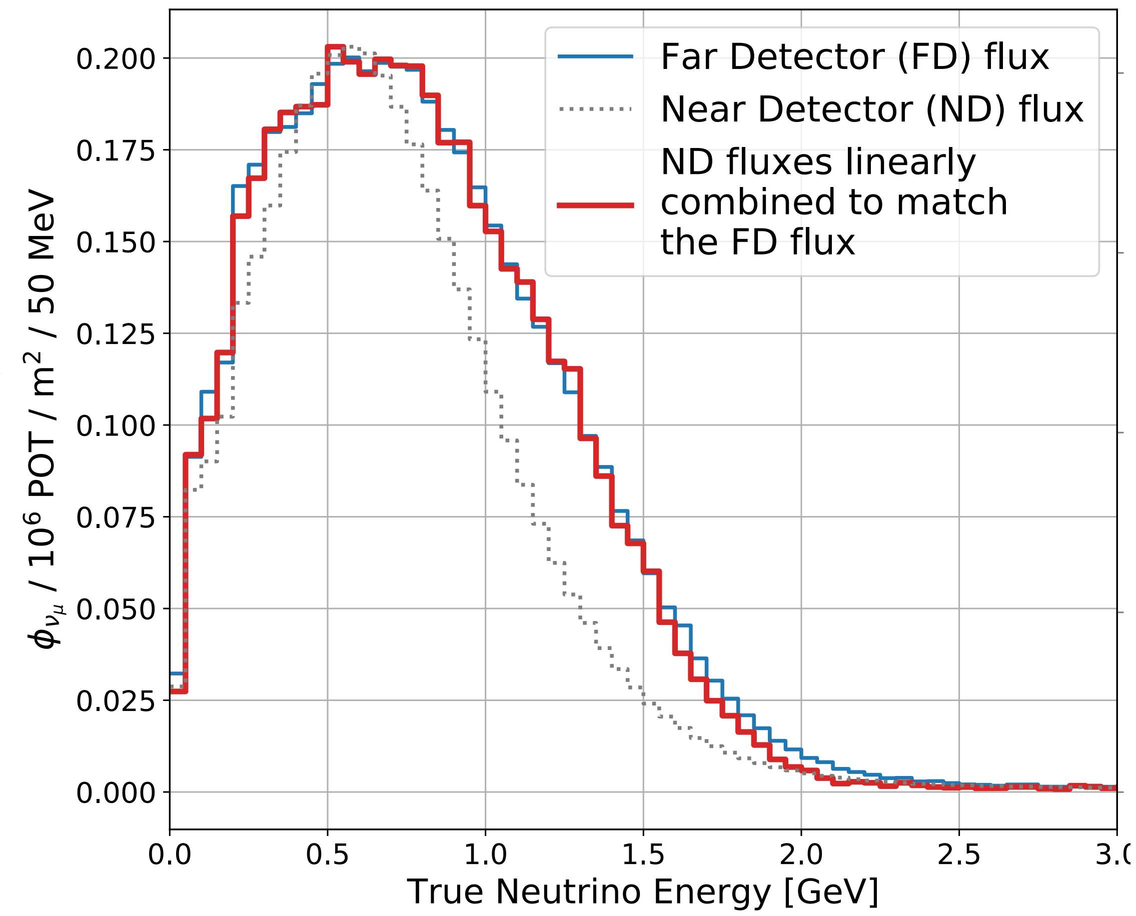
◆ Sterile Neutrino Oscillations

The PRISM feature of SBND can potentially improve the SBN sensitivities to sterile neutrino oscillations. Two possibilities to use the PRISM feature:

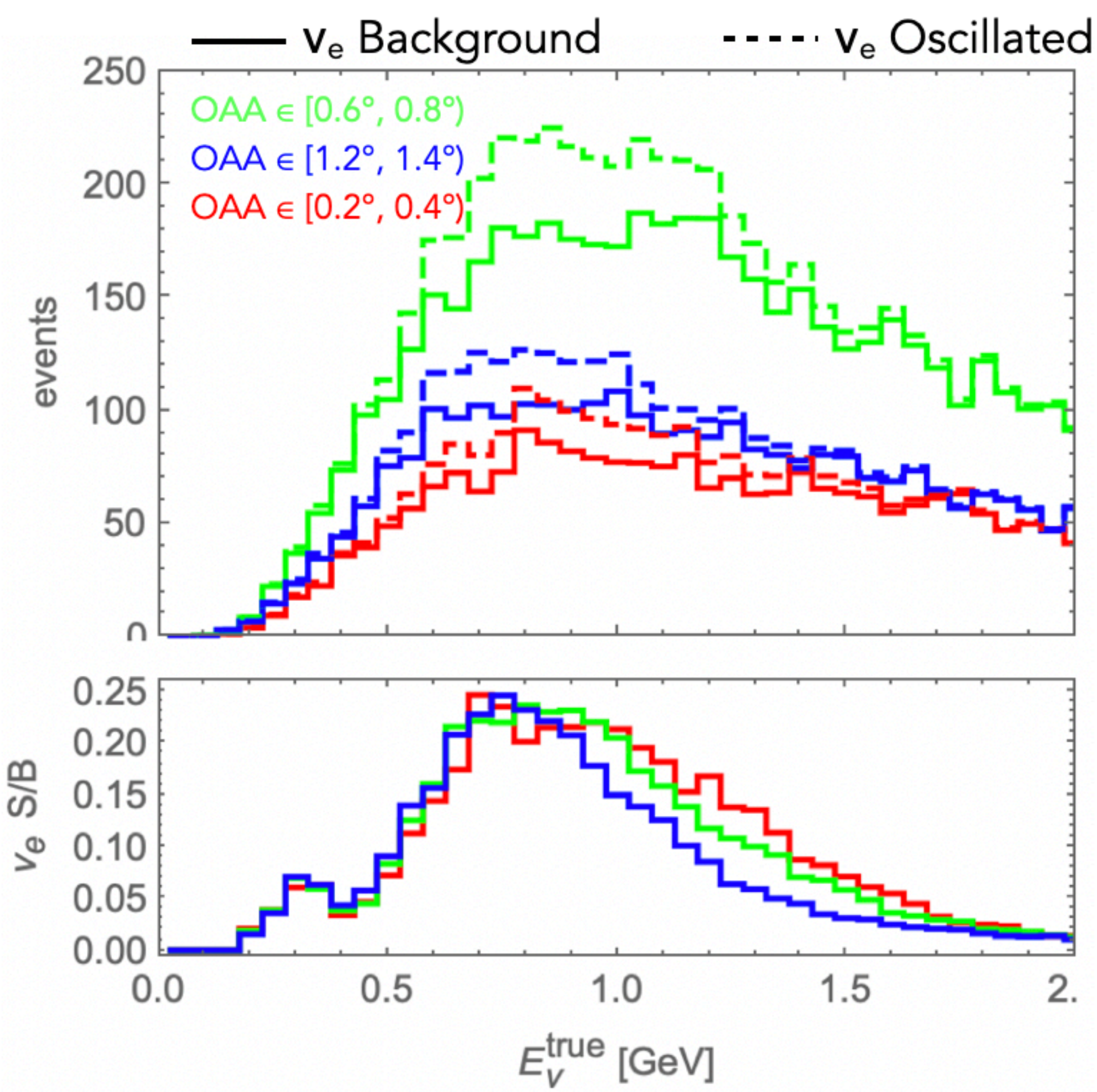
- Instead of treating SBND as a single detector, we can treat it as multiple detectors at different off-axis positions and include those in the **SBN oscillation fit**. Since the energy spectra are different, the neutrino interaction model will be over constrained.

- Can **linearly combine** the measurements at the different off-axis positions to reproduce a given choice of incident neutrino flux. Can match the ICARUS (far detector) oscillated spectrum in SBND (near detector).



◆ Sterile Neutrino Oscillations

- Can we use SBND-PRISM for SBND-only sterile neutrino searches?
  SBND-PRISM potentially allows probing higher values of Δm^2 for sterile neutrino oscillation searches.



Testing sensitivity with:

- $\Delta m^2 = 10\ \mathrm{eV}^2$, $\sin^2 2\theta_{\mu e} = 0.001$
- ν_e appearance mode
- very conservative systematics:
  free norm. + 30% bin-by-bin sys. on bkg

$$\chi^2 = \sum_{i,j}^{\text{pos., bins}} \frac{(N_{ij} + \alpha\, T_{ij})^2}{N_{ij} + \sigma^2_{\text{bin}} N^2_{ij}}$$

w/ PRISM $\chi^2 : 13$

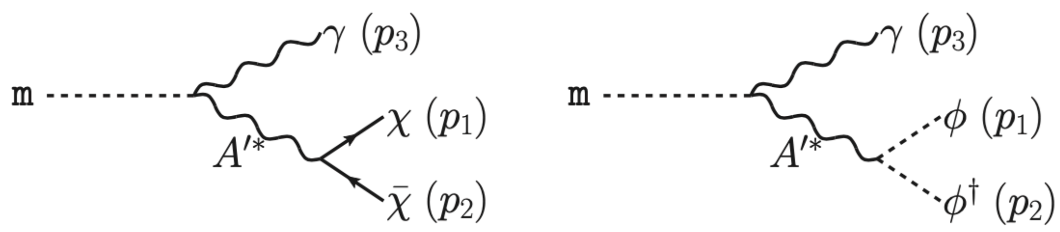
w/o PRISM $\chi^2 : 2$

- Mismatch between ν_μ flux and ν_e contamination on different off-axis positions may be an opportunity to probe this physics.

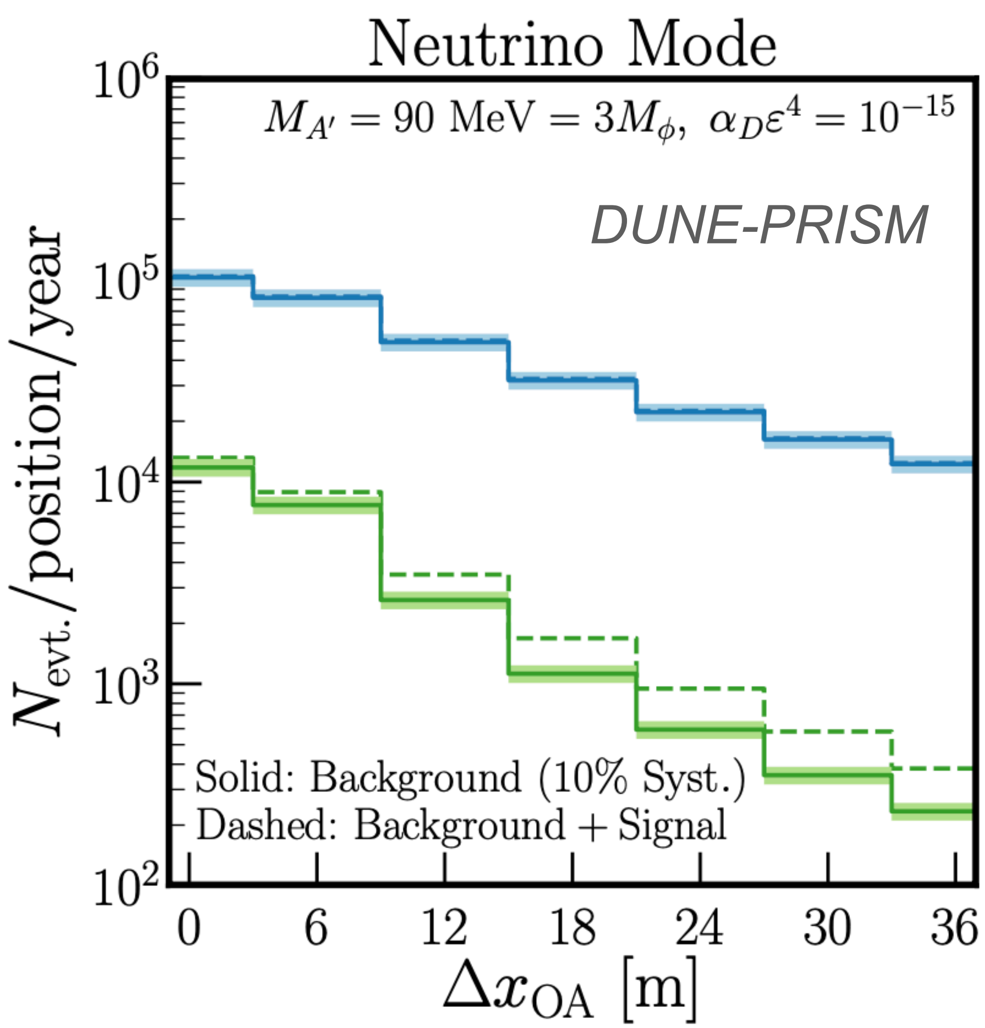
- Proper estimation of systematics is needed before final conclusions can be made, but results look promising with current (conservative) systematic guess.

SBND-PRISM: Dark Matter Searches

◆ **Light (sub-GeV) Dark Matter**

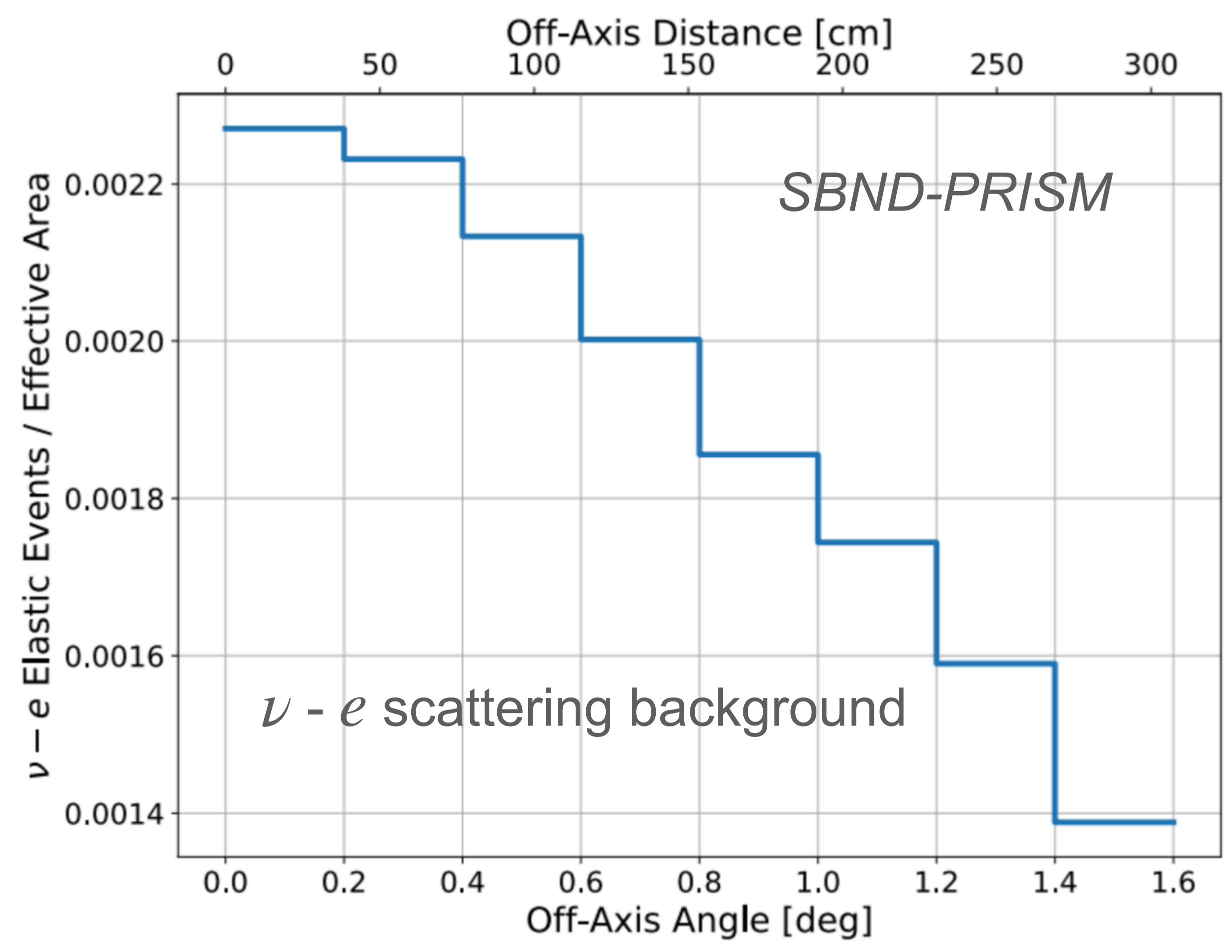


- Produced via the decay of neutral mesons (no focusing) produced at the beam target.
- The DM-signal to neutrino-background ratio increases as a function of OAA.



V. De Romeri, K. J. Kelly, P. A. N. Machado, [arXiv:1903.10505 [hep-ph]]

- For the DM-electron scattering signal, ν - e scattering is one of the primary background.



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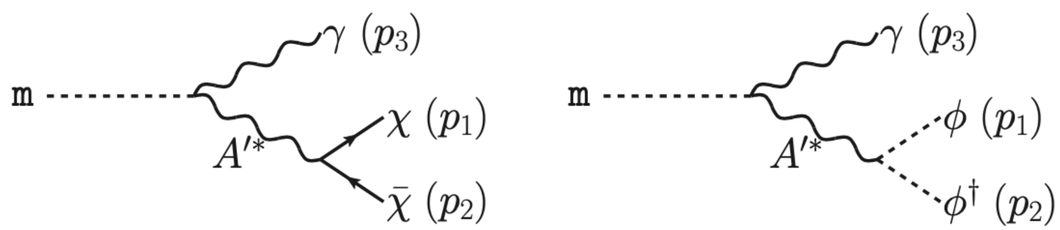

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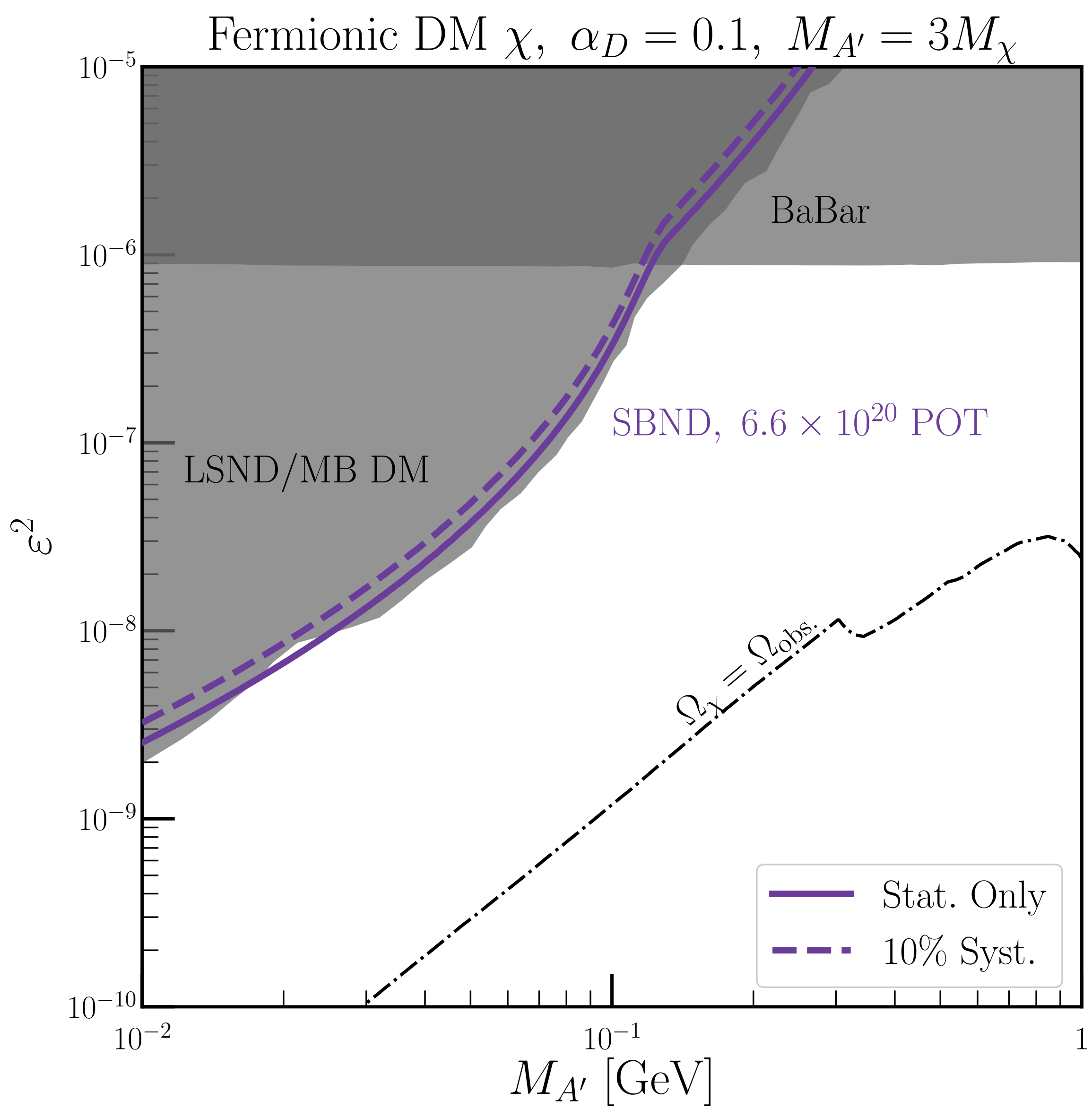

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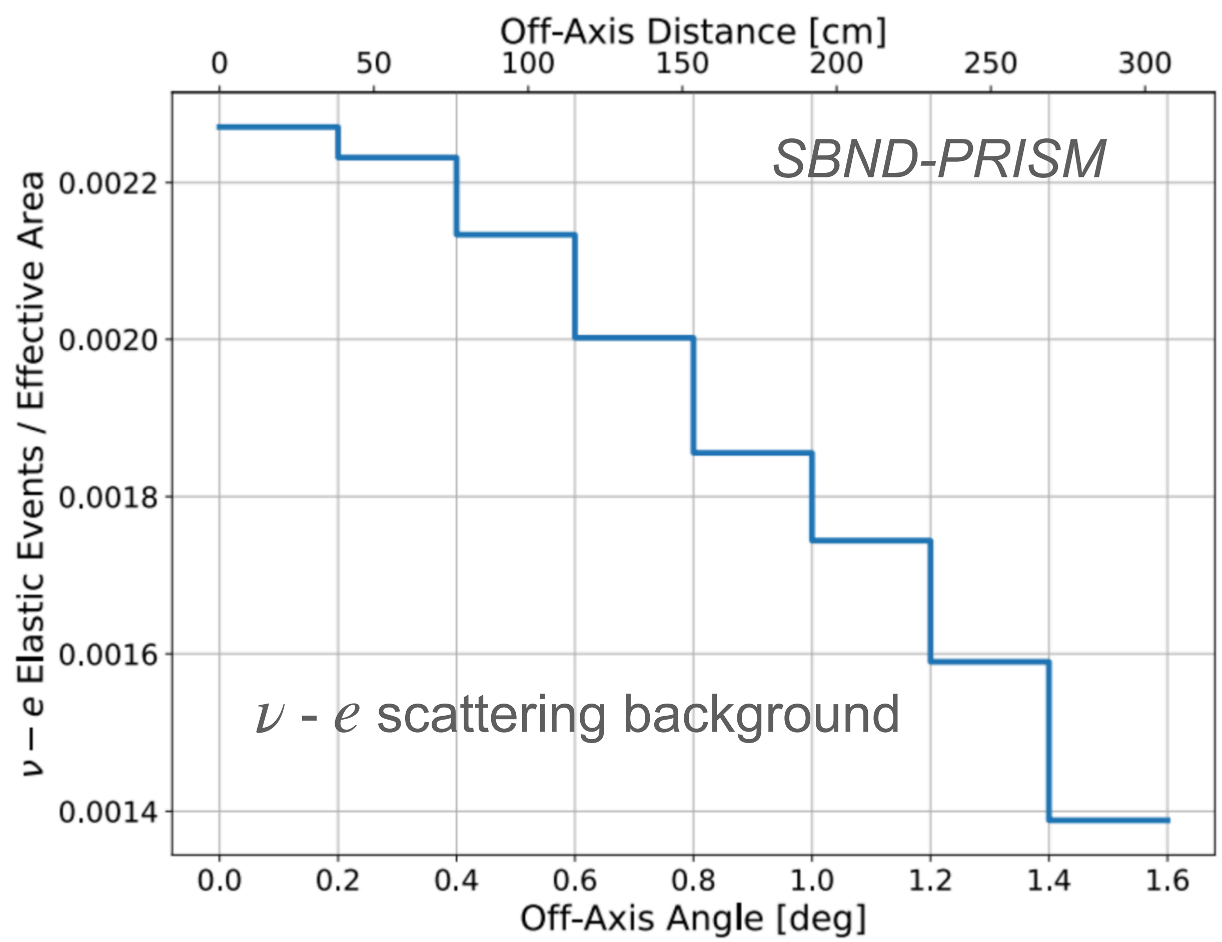
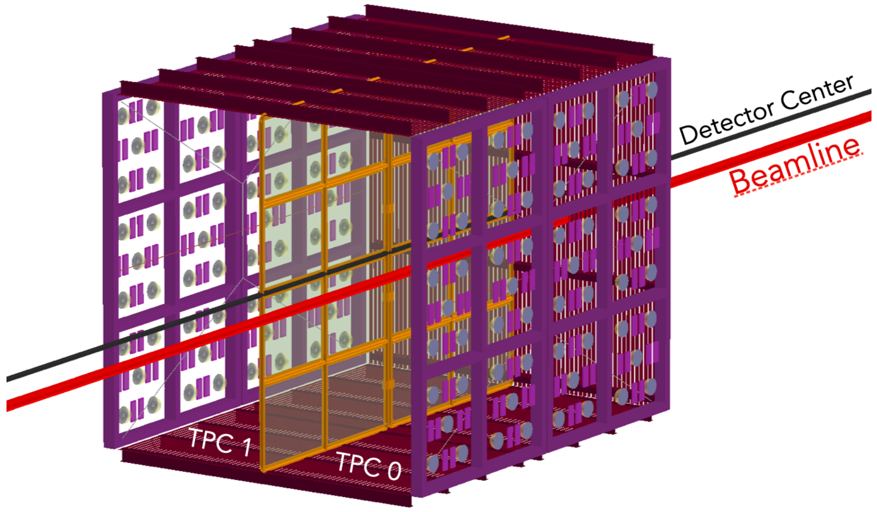
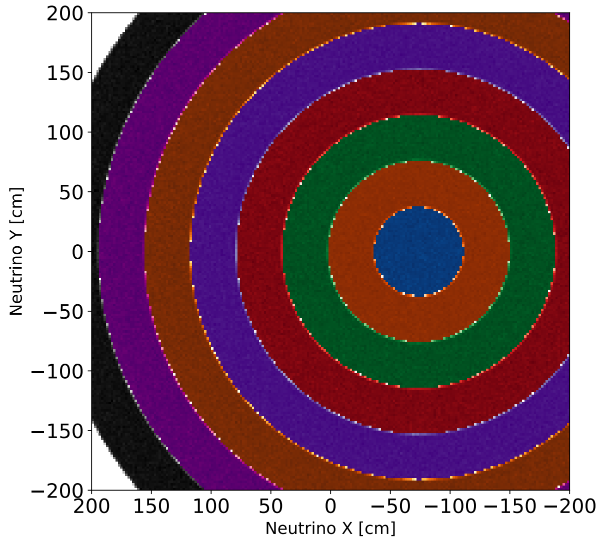


- Not yet included:
  - electron recoil energy information to discriminate signal vs. background, that is expected to further improve the sensitivity.
  - effects of dividing the detector into off-axis angular bins.

Summary

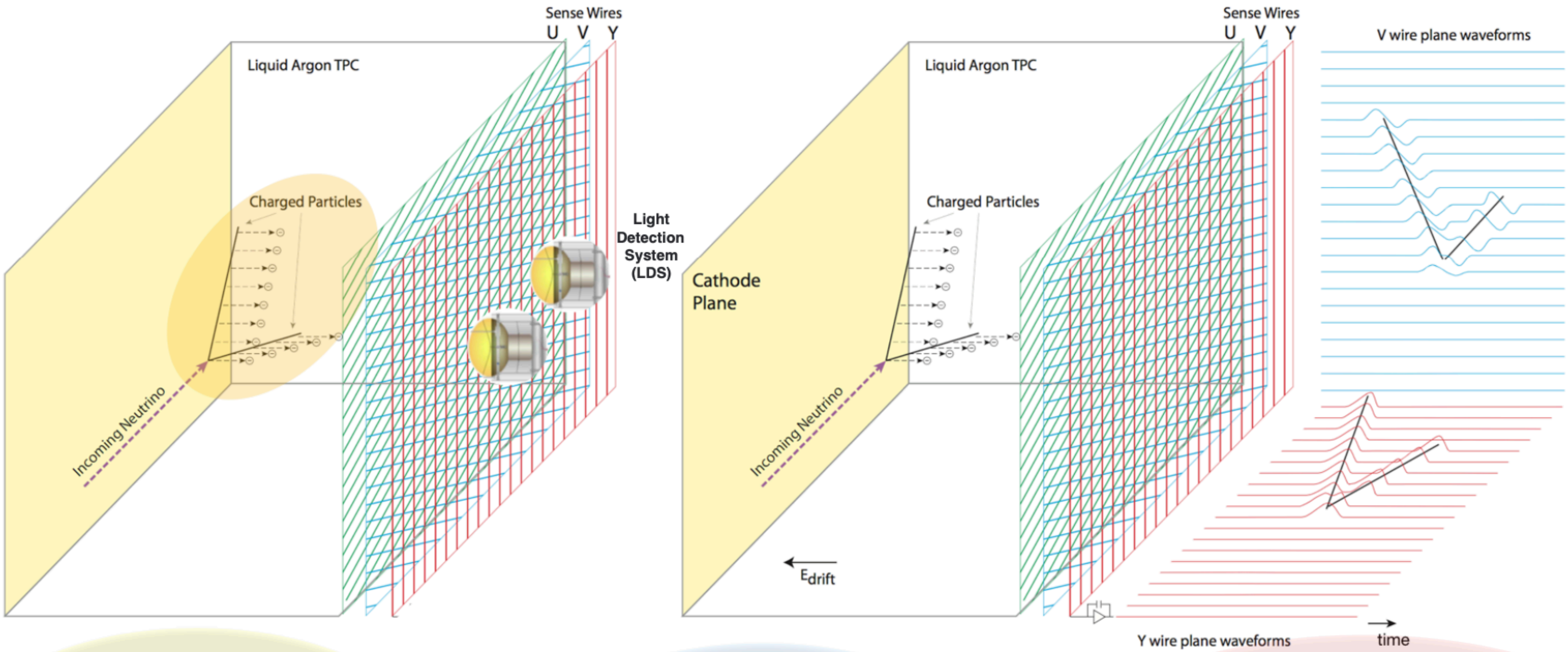
- SBND, currently under construction, is the near detector of the SBN program at Fermilab.
- SBND has a rich neutrino-nucleus cross sections, and BSM physics program.
- The proximity of the SBND to the neutrino target source, combined with the abundance of statistics allows us to use a "free" SBND-PRISM feature.
- SBND can take data on all the off-axis regions simultaneously.
- SBND-PRISM could constrain the relationship between true and reconstructed energy and potentially help disentangling the effects due to mismodeling of the neutrino flux, neutrino interaction cross-sections, and detector response.
- SBND-PRISM opens up new possibilities: can potentially constrain neutrino-nucleus interaction modeling, improve oscillation fits, allows for an SBND-only oscillation analysis, and other BSM searches.





Additional-Material

LArTPC: Operating Principle



Charged particles in LAr produce free ionization electrons and scintillation light

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge]

m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

Scintillation light **fast** signals from LDSs give event timing